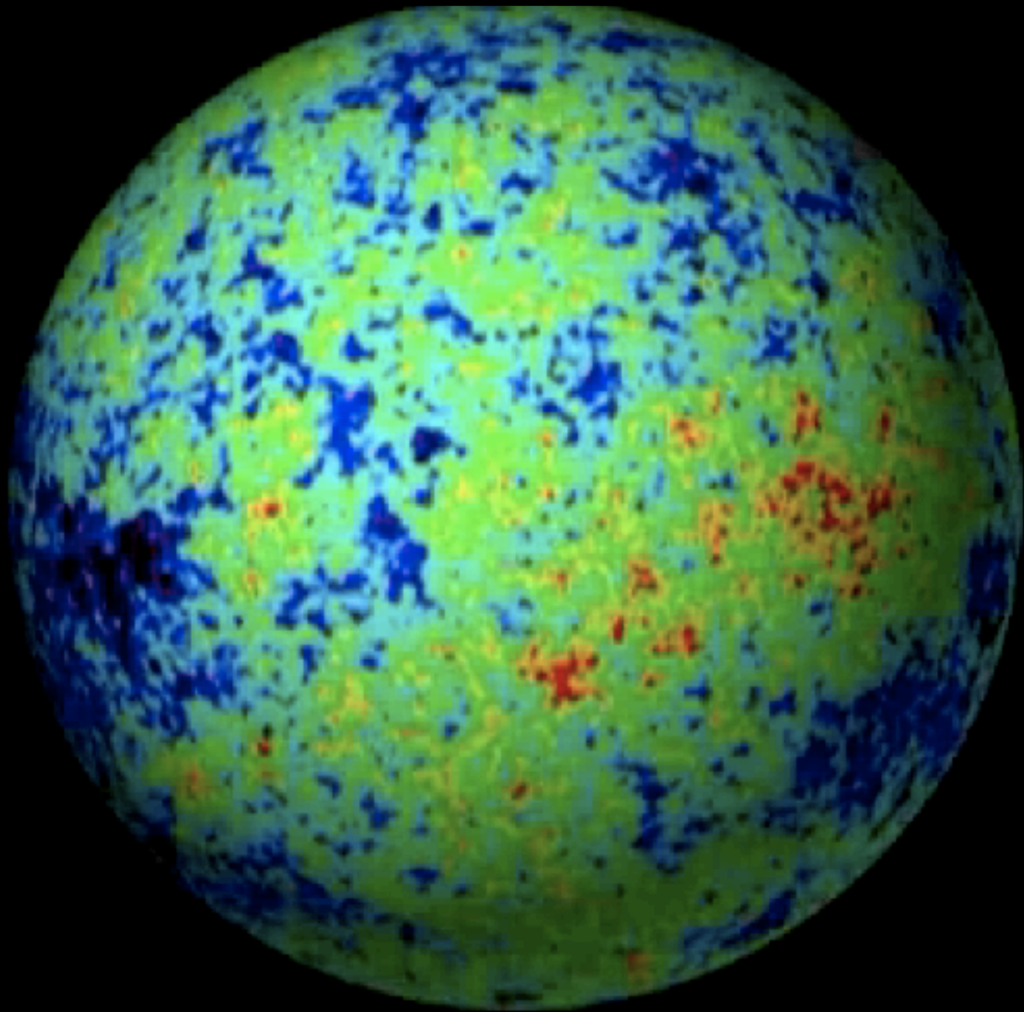
Cosmology & Particle Physics



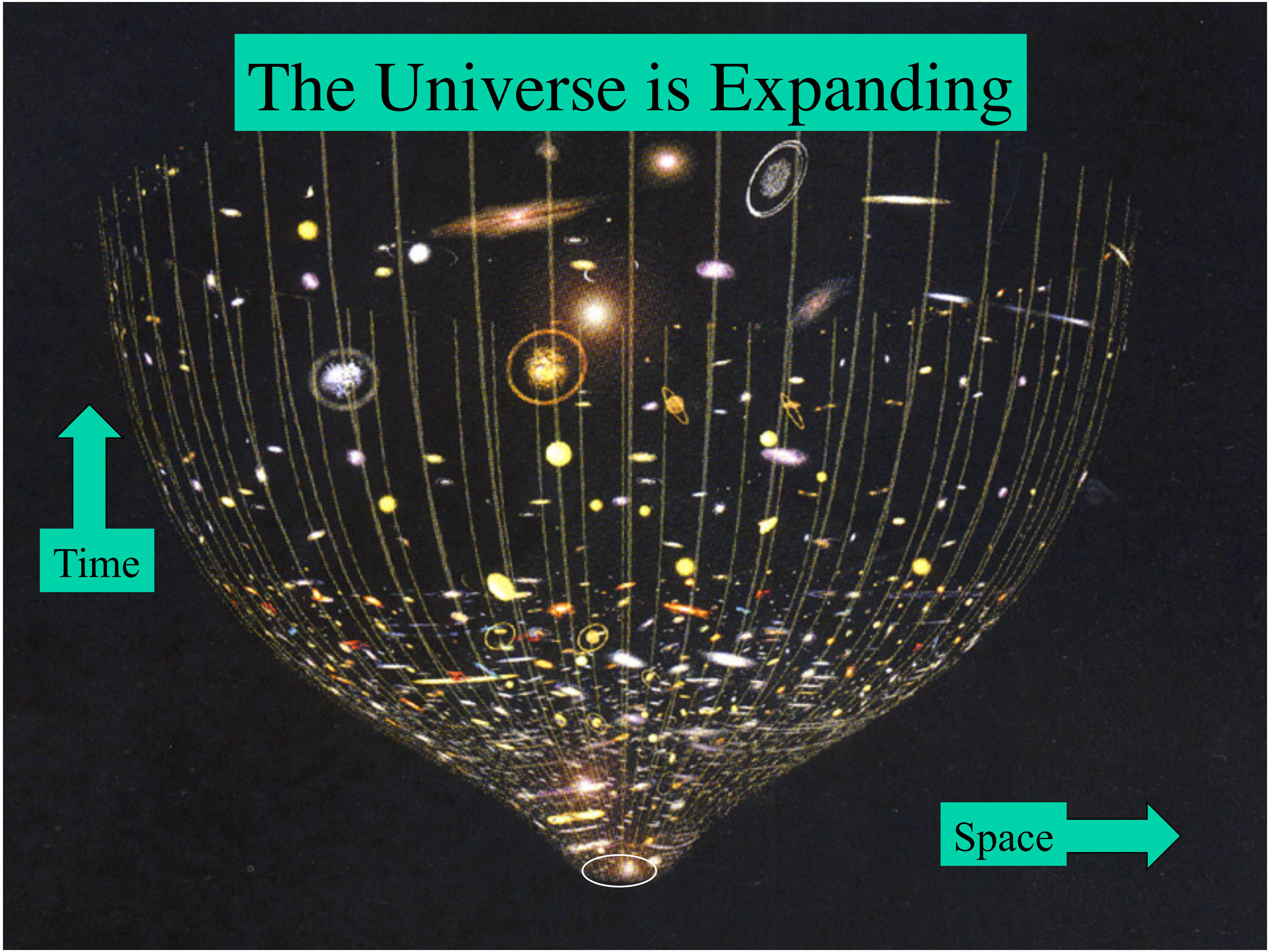
John Ellis
King's College London & CERN

Plan of Lectures

1 - The Big Picture
- Introduction to Big Bang cosmology
- Dark matter and dark energy
- The role of particle physics in the early Universe

2 – Particle candidates for dark matter and dark energy
- The Higgs boson and cosmology
- Supersymmetry
- Searching for supersymmetry at the LHC
- Searches for supersymmetric dark matter

The Universe is Expanding



Olbers' Paradox

- Why is the night sky not as bright as the surface of the Sun?
- In an infinite, static Universe, every line of sight would end at the surface of a star
- Absorption does not help (Herschel)
- Finite spherical Universe no help either
- Universe must be finite in time and/or space

The Universe is expanding

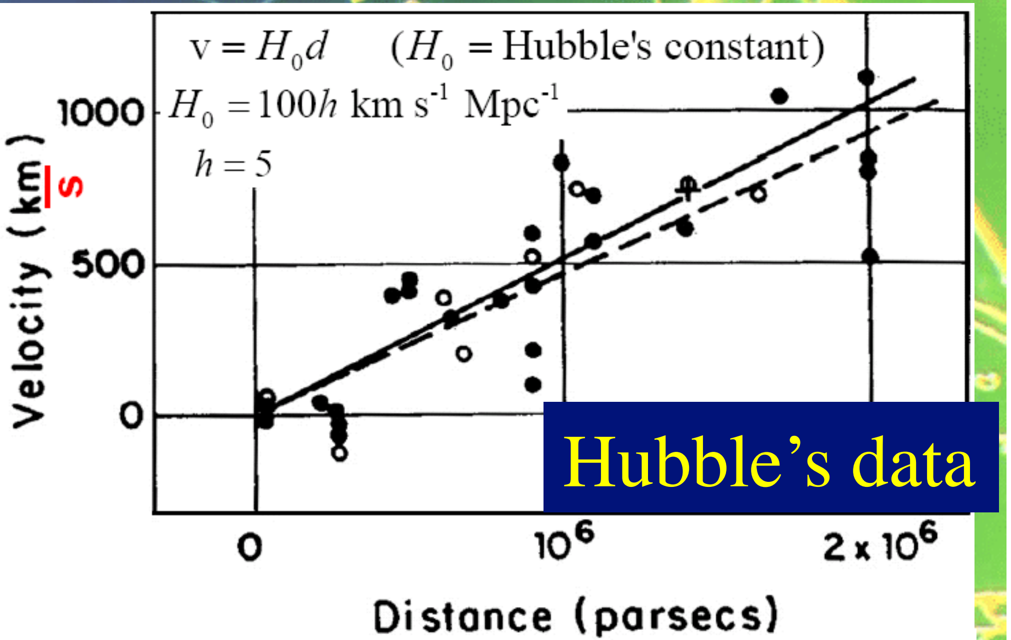
- Galaxies are receding from us

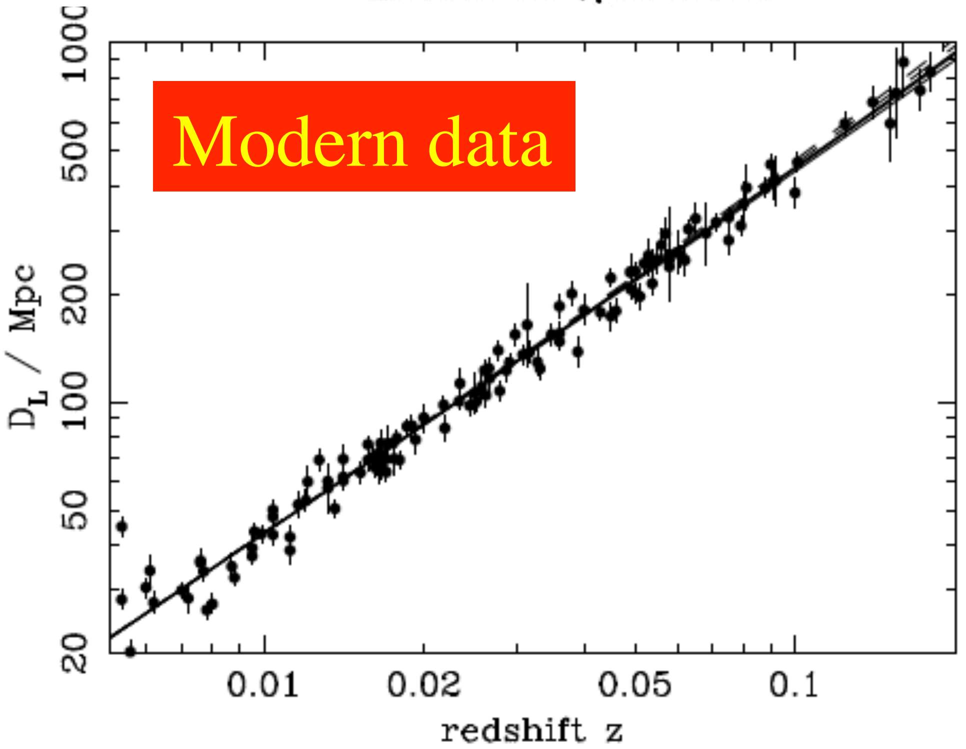
  Hubble expansion law: galactic redshifts

The expansion of the Universe

Hubble, basketball player

University of Chicago 1909 National Champions





The Universe is expanding

- Galaxies are receding from us

  Hubble expansion law: galactic redshifts

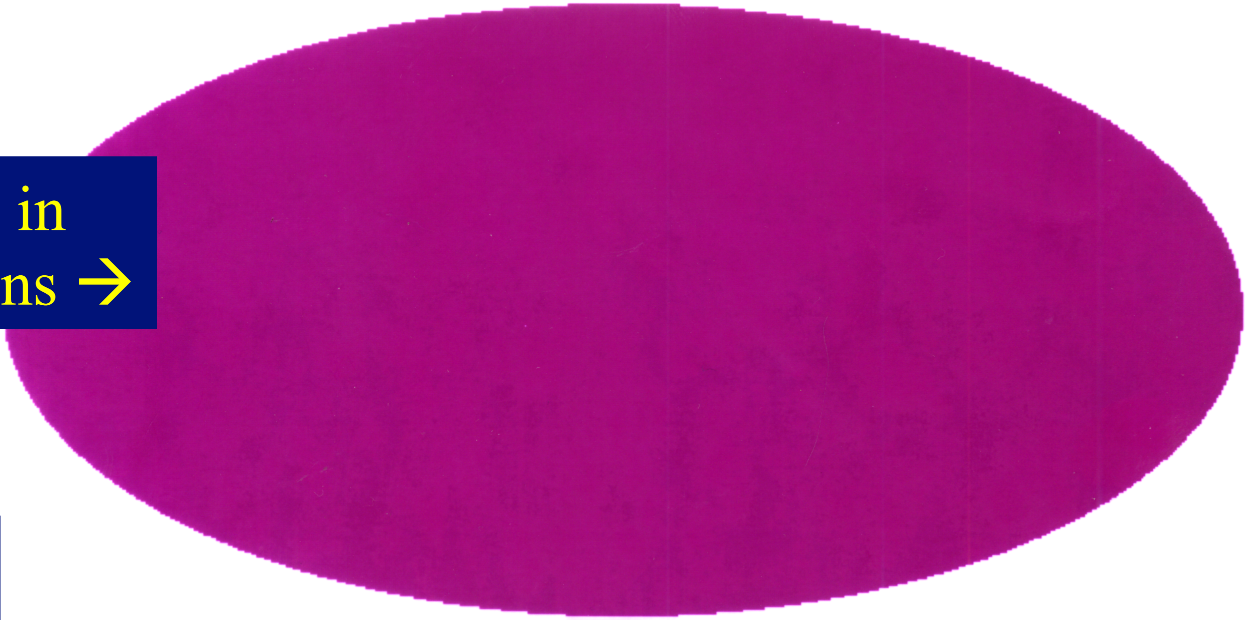
- The Universe was once 3000 smaller, hotter than today

  cosmic microwave background radiation

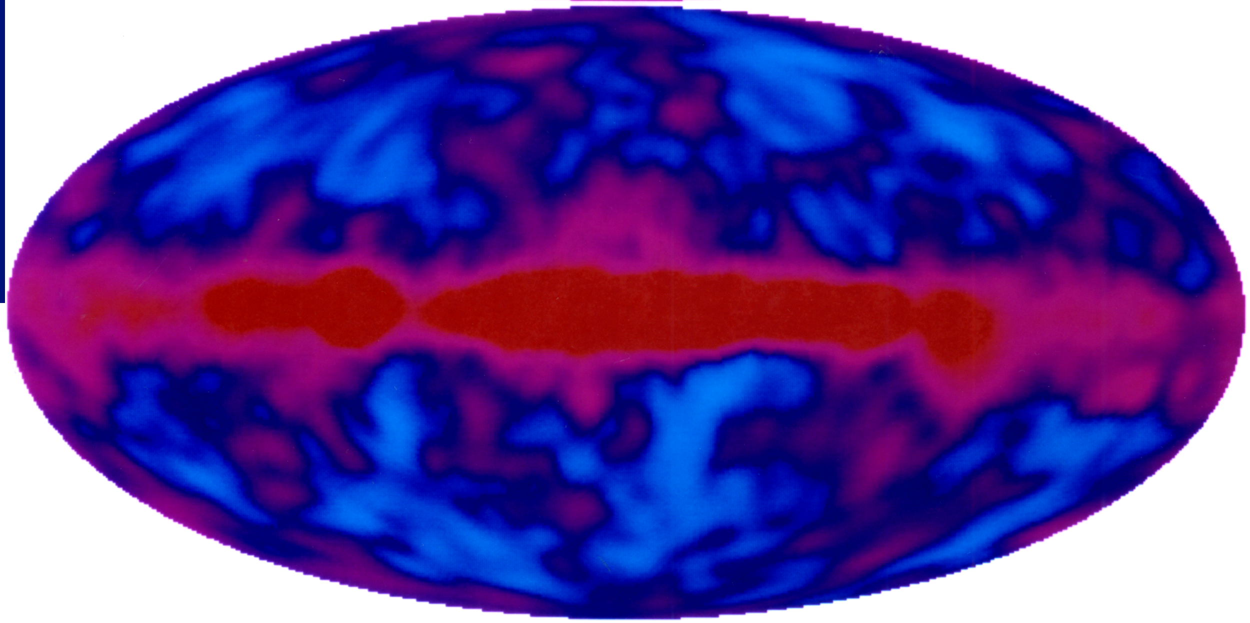
  emitted from the primordial plasma

Cosmic Microwave Background

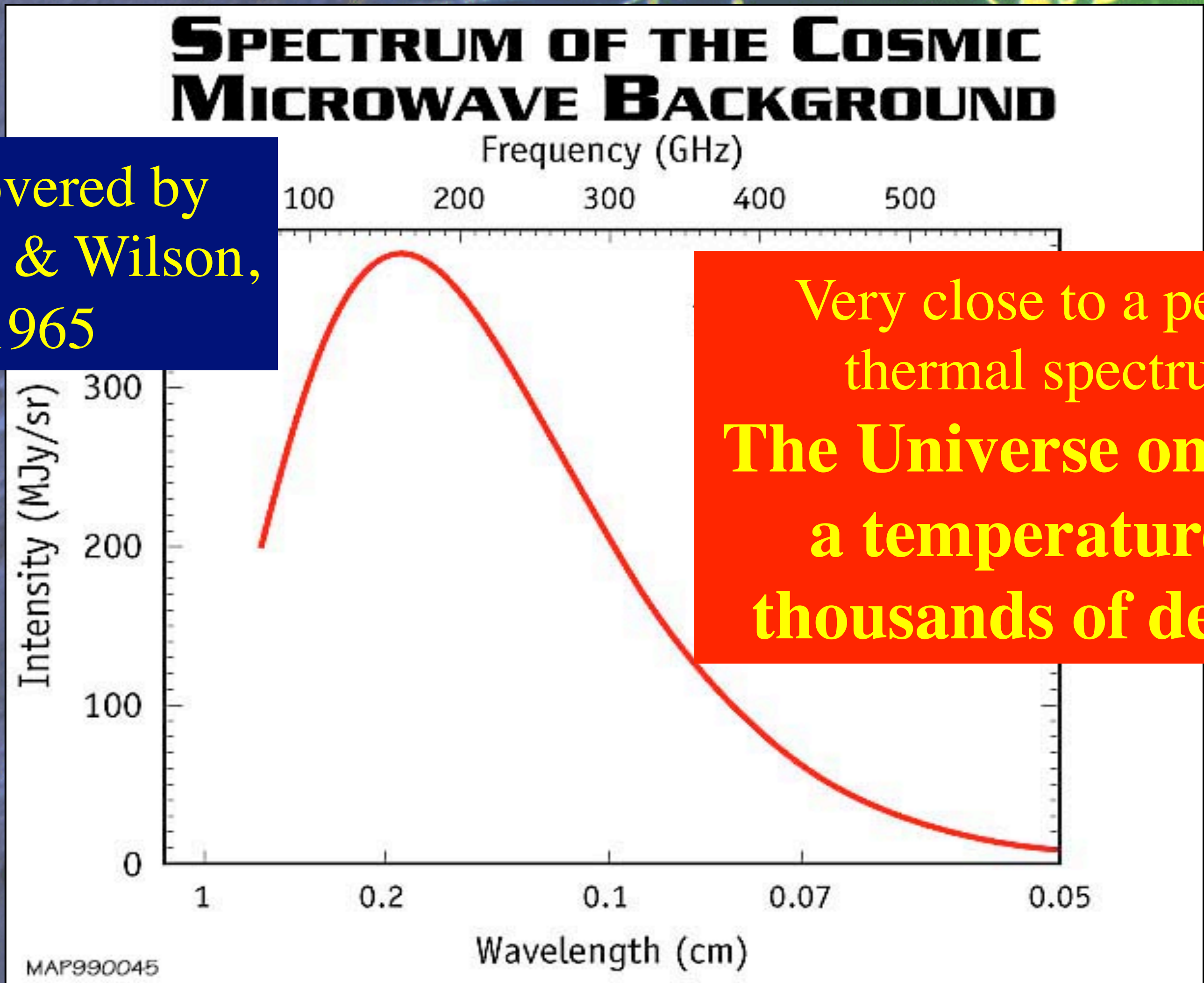
Almost the same in different directions →



Small variations discovered by COBE satellite →



The Cosmic Microwave Background Radiation



Discovered by Penzias & Wilson, 1965

Very close to a perfect thermal spectrum:

The Universe once had a temperature of thousands of degrees

The Universe is expanding

- Galaxies are receding from us

  Hubble expansion law: galactic redshifts
- The Universe was once 3000 smaller, hotter than today

  cosmic microwave background radiation
- The Universe was once a billion times smaller, hotter than today

  light elements cooked in the Big Bang

Making Elements in the Early Universe

- Universe contains about 24% Helium 4

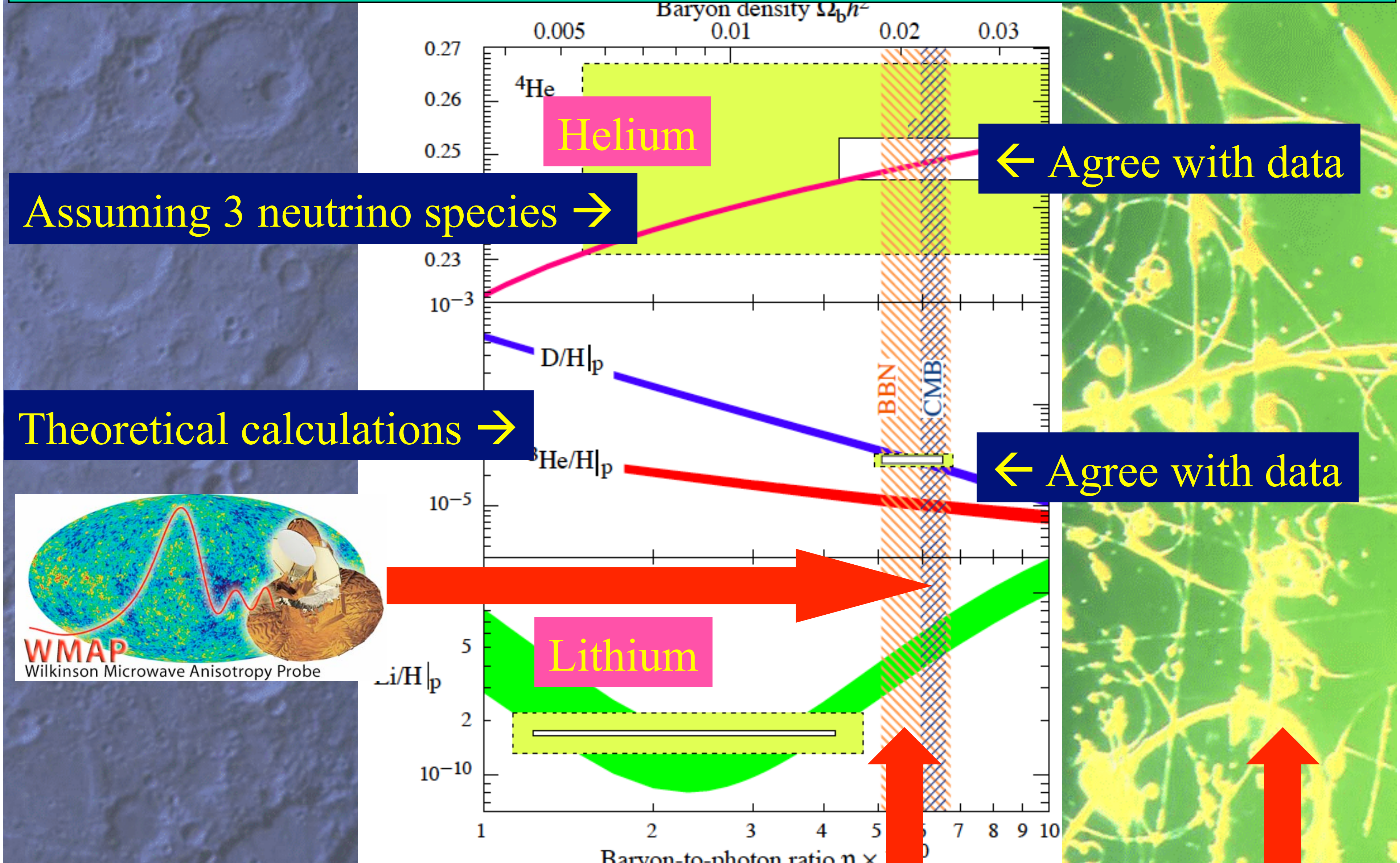
  and less Deuterium, Helium 3, Lithium 7
- Could only have been cooked by nuclear reactions in dense early Universe

  when Universe billion times smaller, hotter than today
- Dependent on amount of matter in Universe

  not enough to stop expansion, explain galaxies
- Dependent on number of particle types

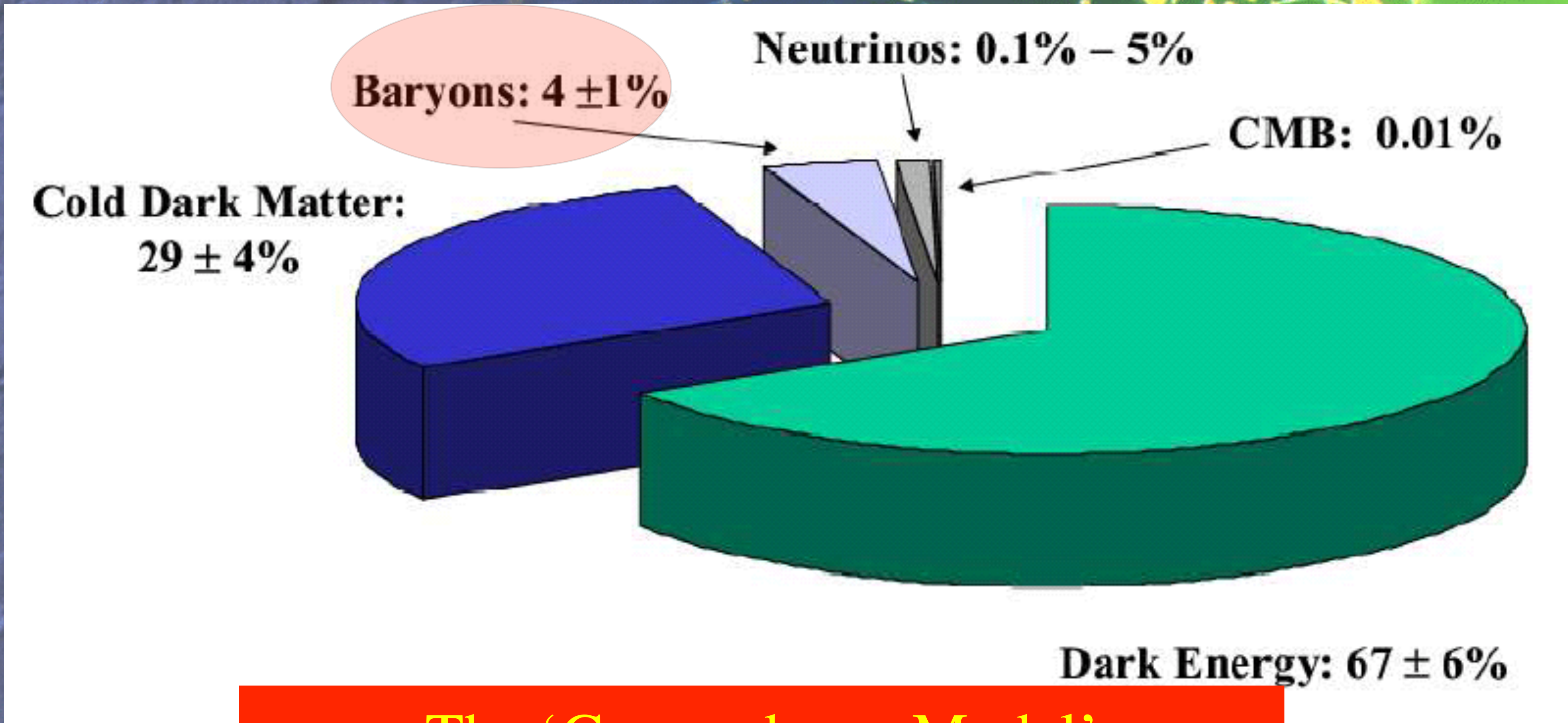
  number of different neutrinos measured at accelerators

Abundances of light elements in the Universe



Not enough ordinary matter to make the Universe recollapse

A Strange Recipe for a Universe



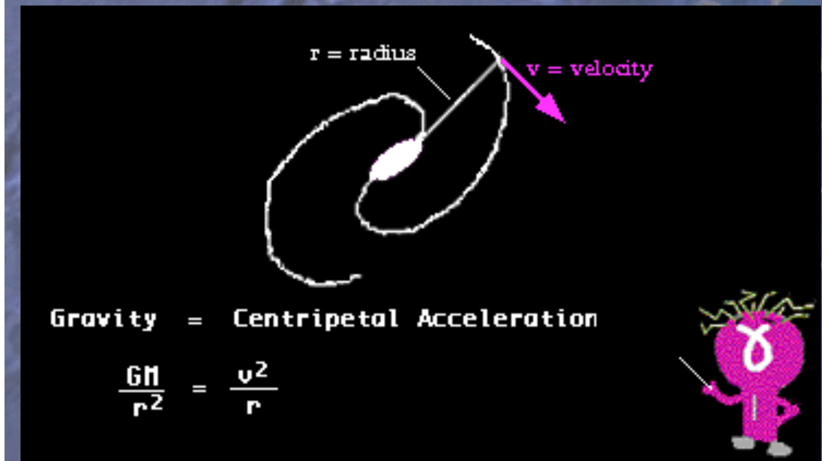
The 'Concordance Model'
prompted by astrophysics & cosmology

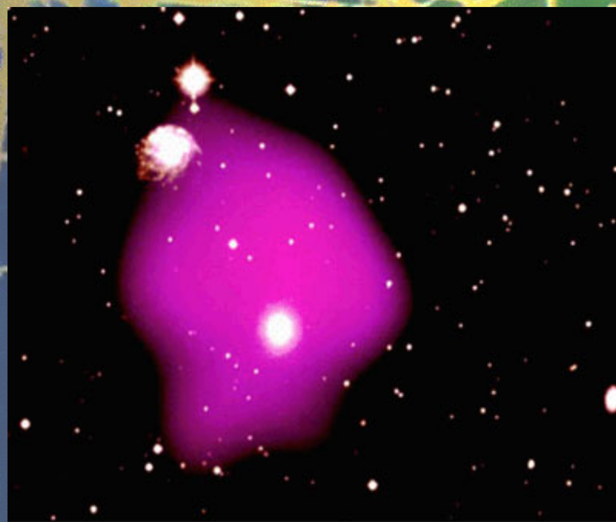
Evidence for Dark Matter

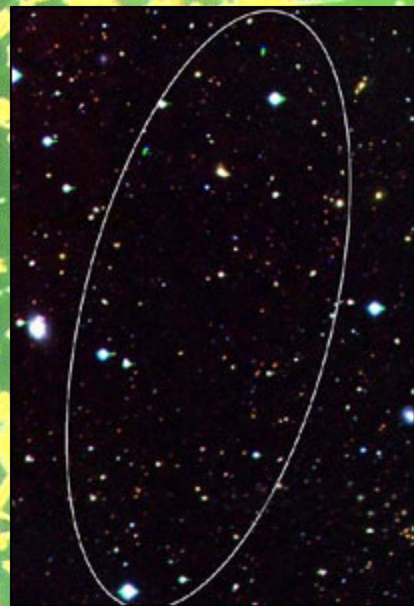
Galaxies rotate more rapidly than allowed by centripetal force due to visible matter

X-ray emitting gas held in place by extra dark matter

Even a ‘dark galaxy’ without stars



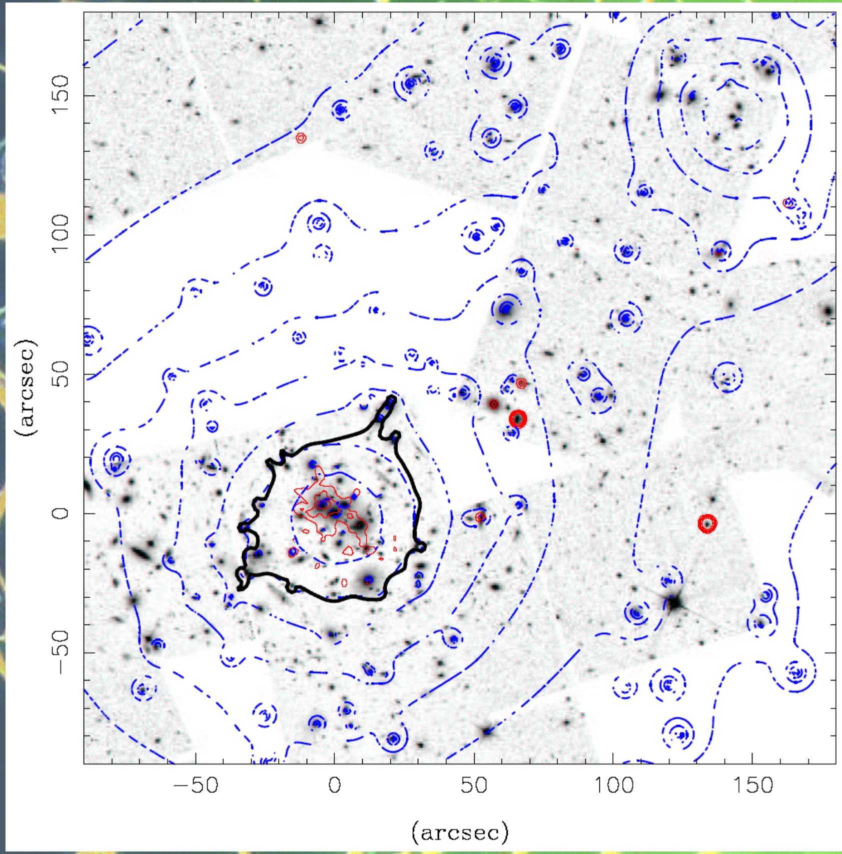




Evidence for Dark Matter from Gravitational Lensing

Light bent by gravitational field of dark matter

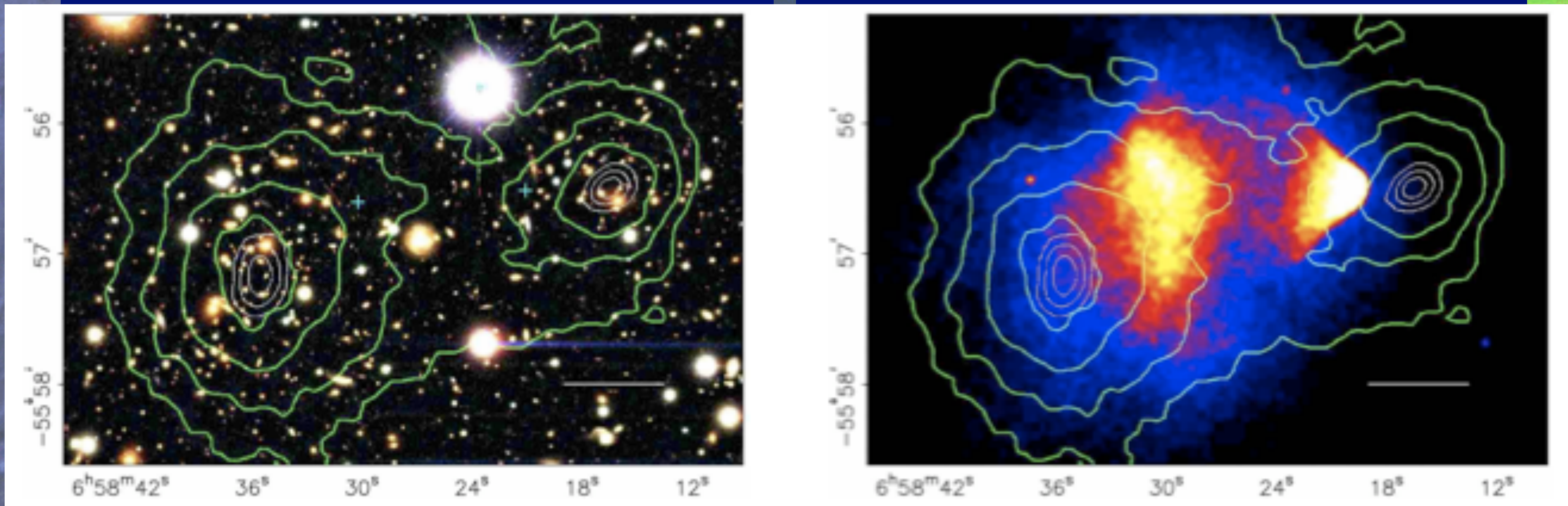
Contours of mass density



Direct Evidence for Collisionless Dark Matter

Collision of two galaxies:
dark matter lumps pass through

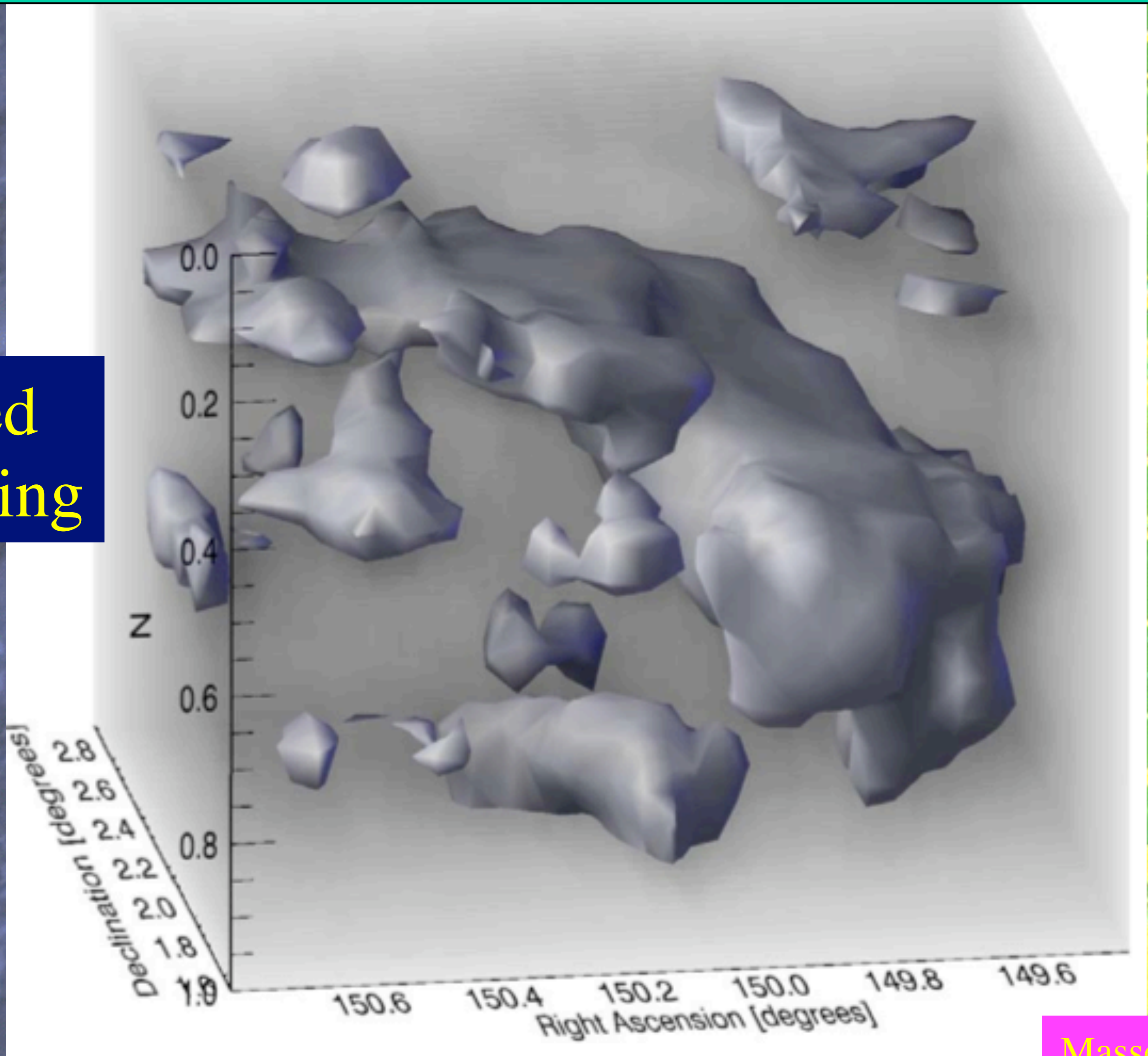
Collision of two galaxies:
gaseous matter stuck in between



Clowe et al, 2006

The Dark Matter Scaffolding

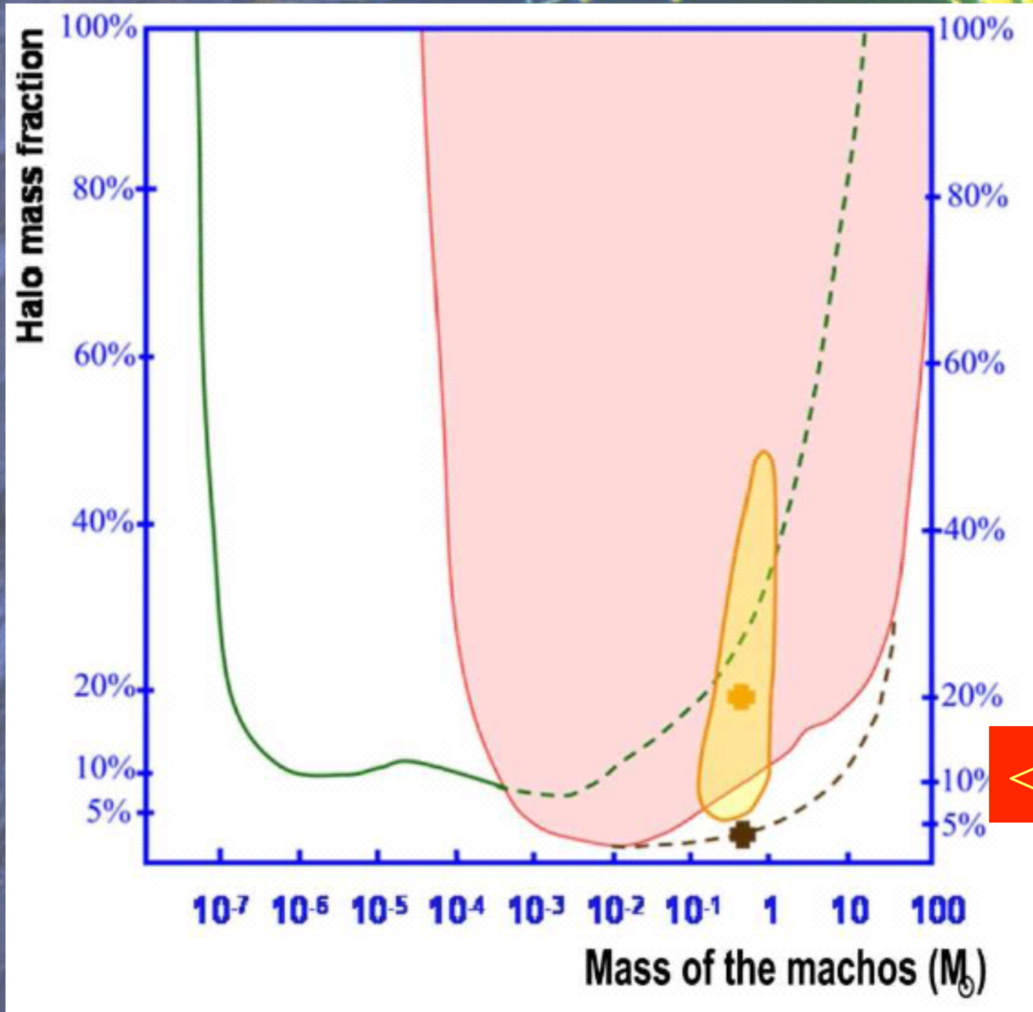
As measured by weak lensing



Massey et al, 2007

Could our galactic halo be ordinary matter?

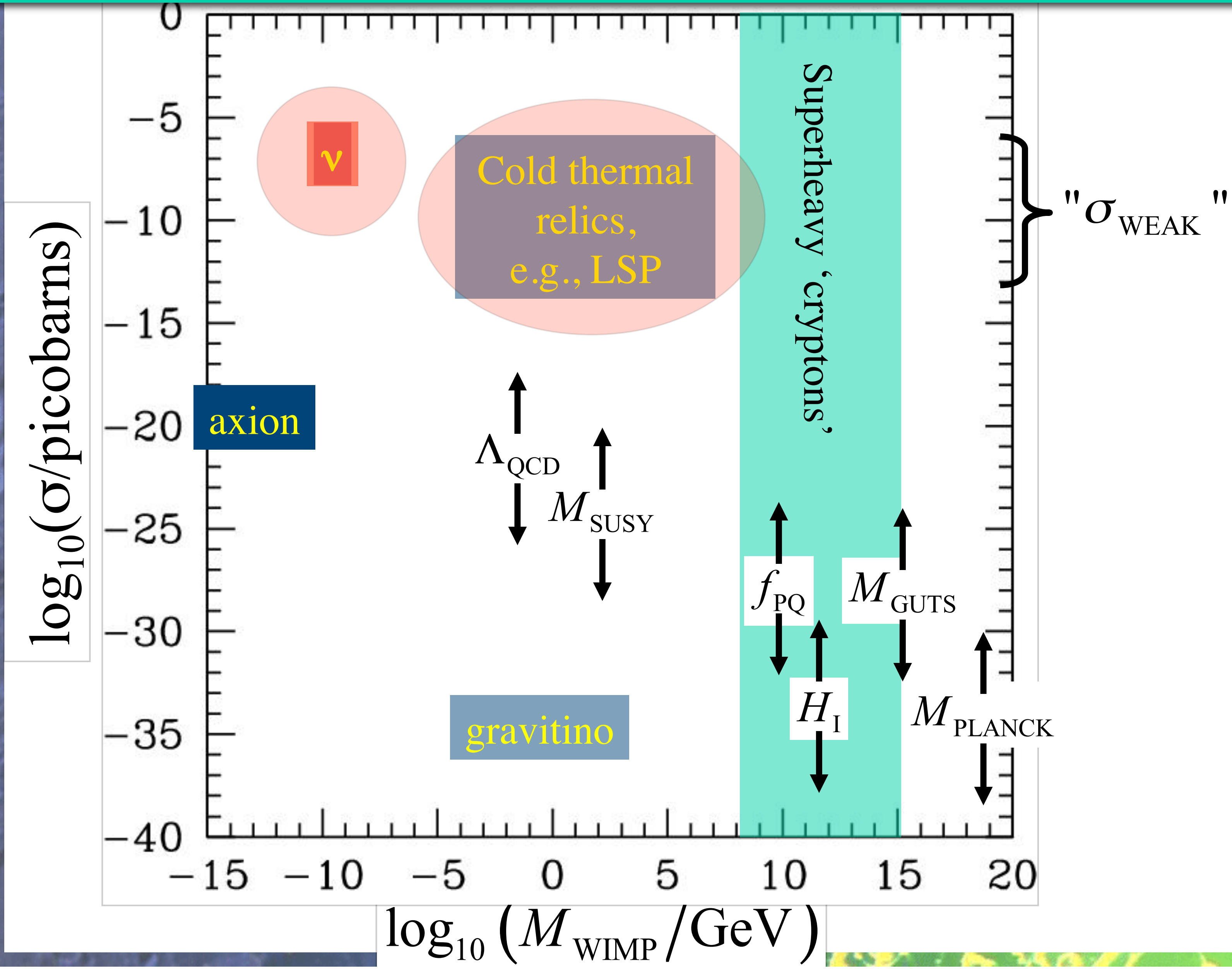
Our Halo is not made of Machos



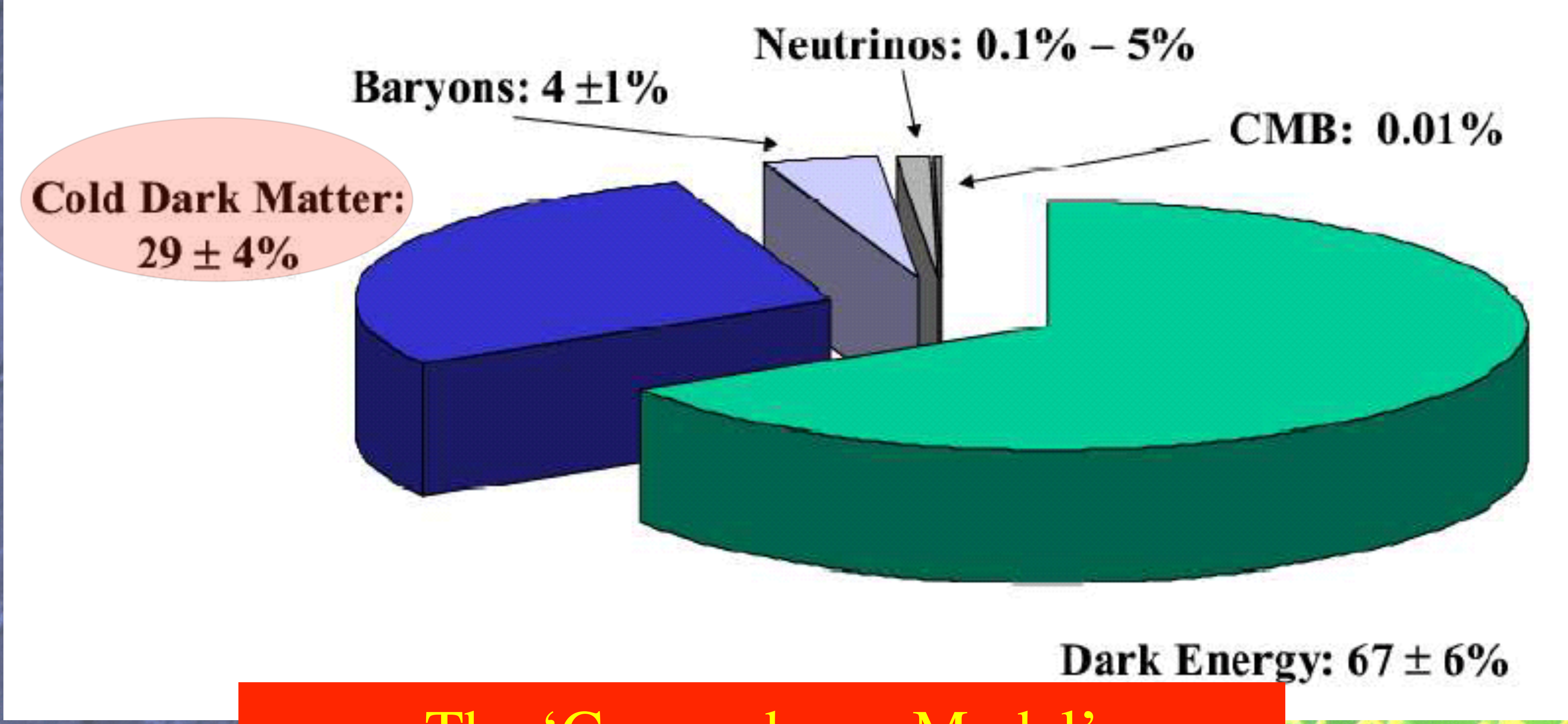
= MAssive
Compact
Halo
Objects
= dead stars
or black holes

< 10 % of our halo

Particle Dark Matter Candidates



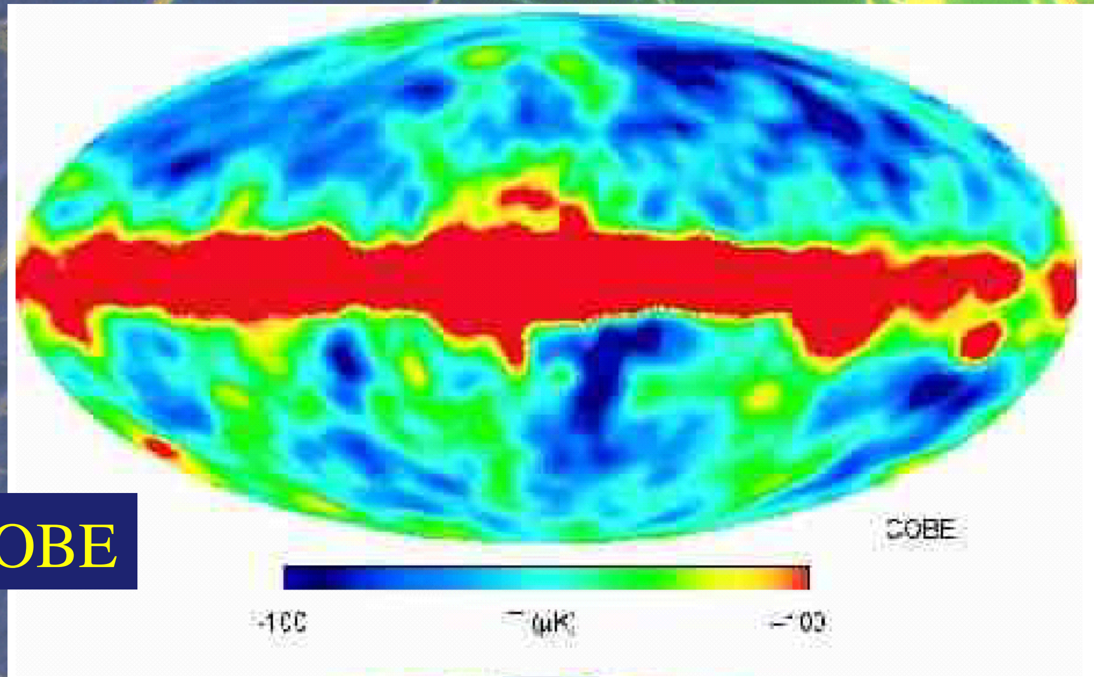
A Strange Recipe for a Universe

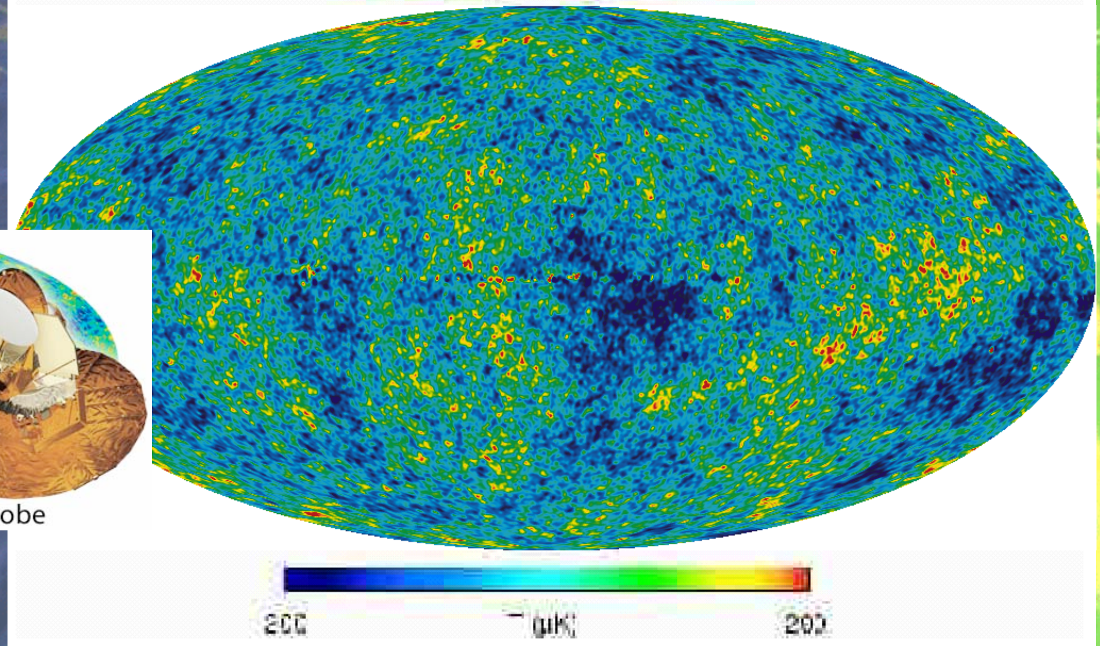


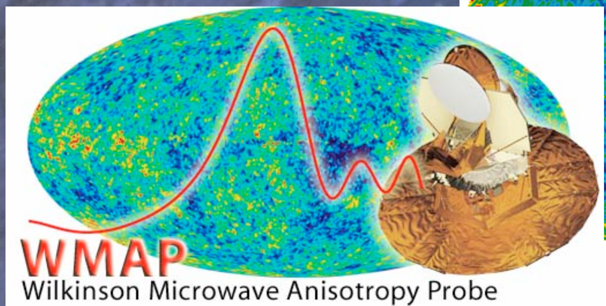
The 'Concordance Model'
prompted by astrophysics & cosmology

The Cosmic Microwave Background

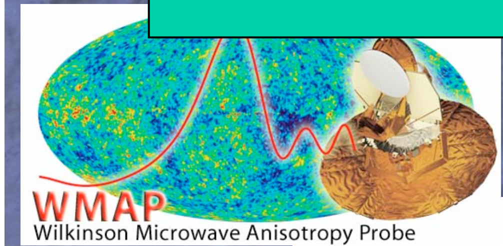
According to COBE





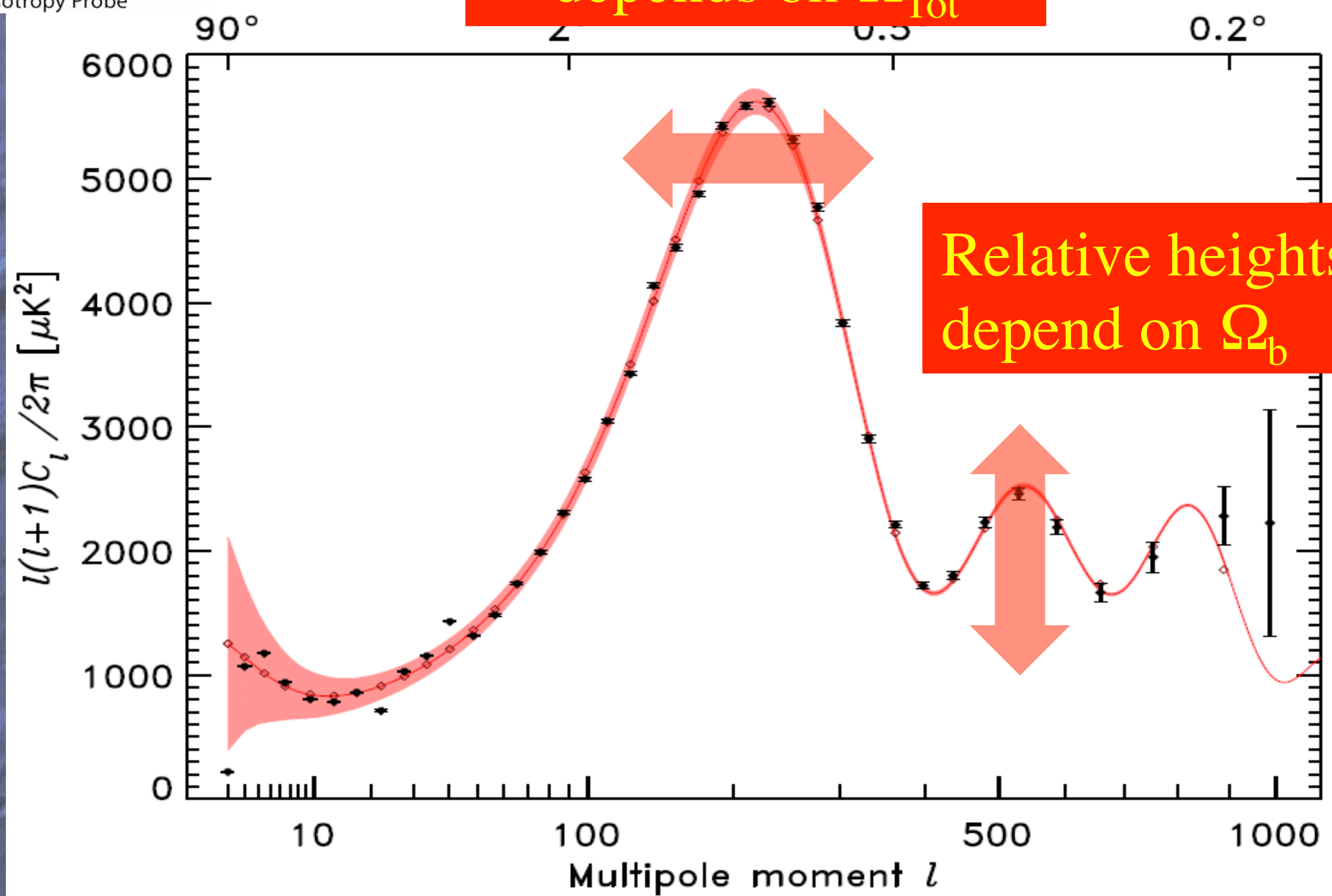


The CMB Power Spectrum

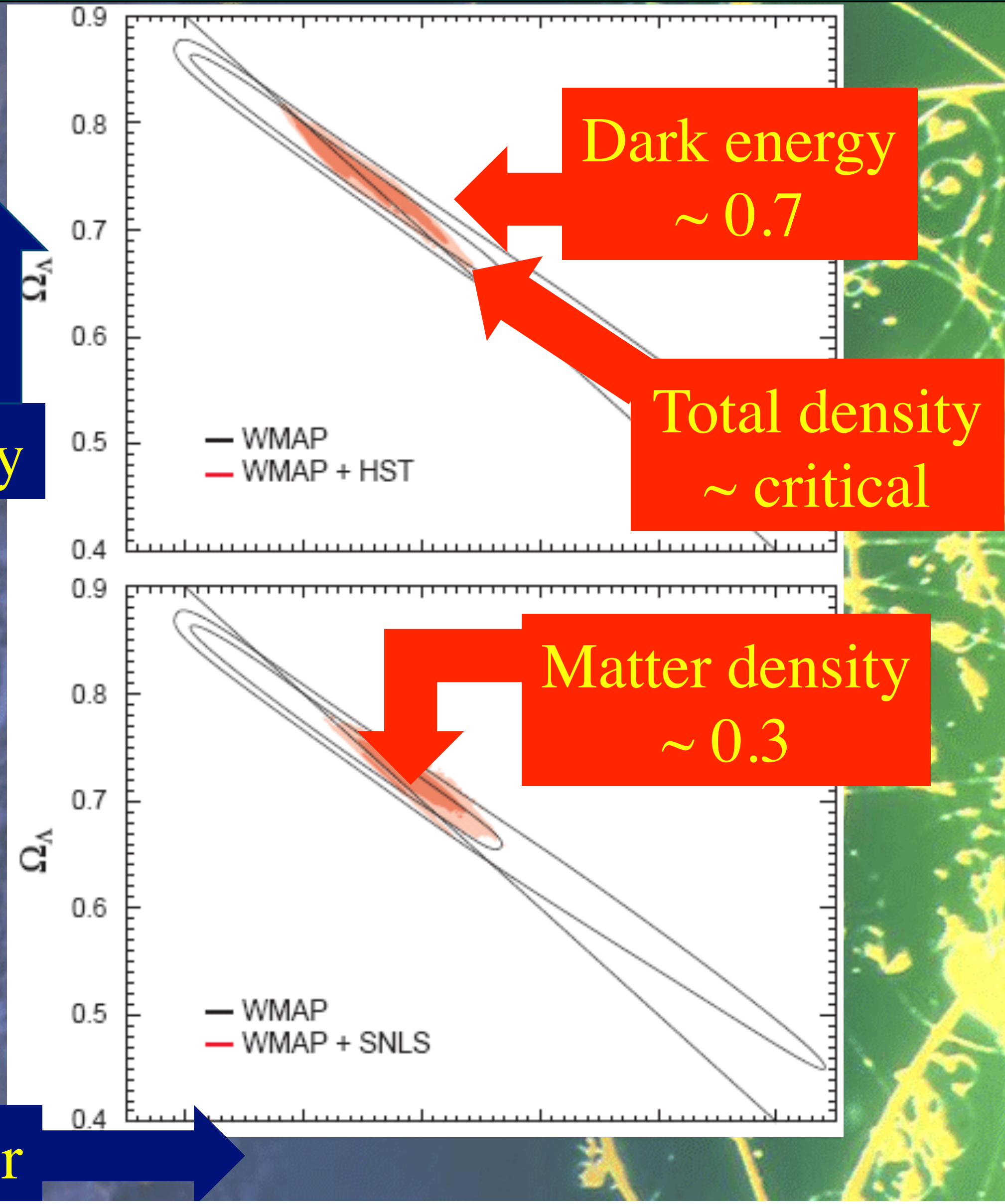


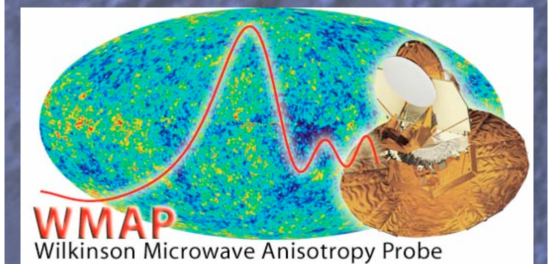
Location of first peak depends on Ω_{Tot}

Relative heights depend on Ω_b

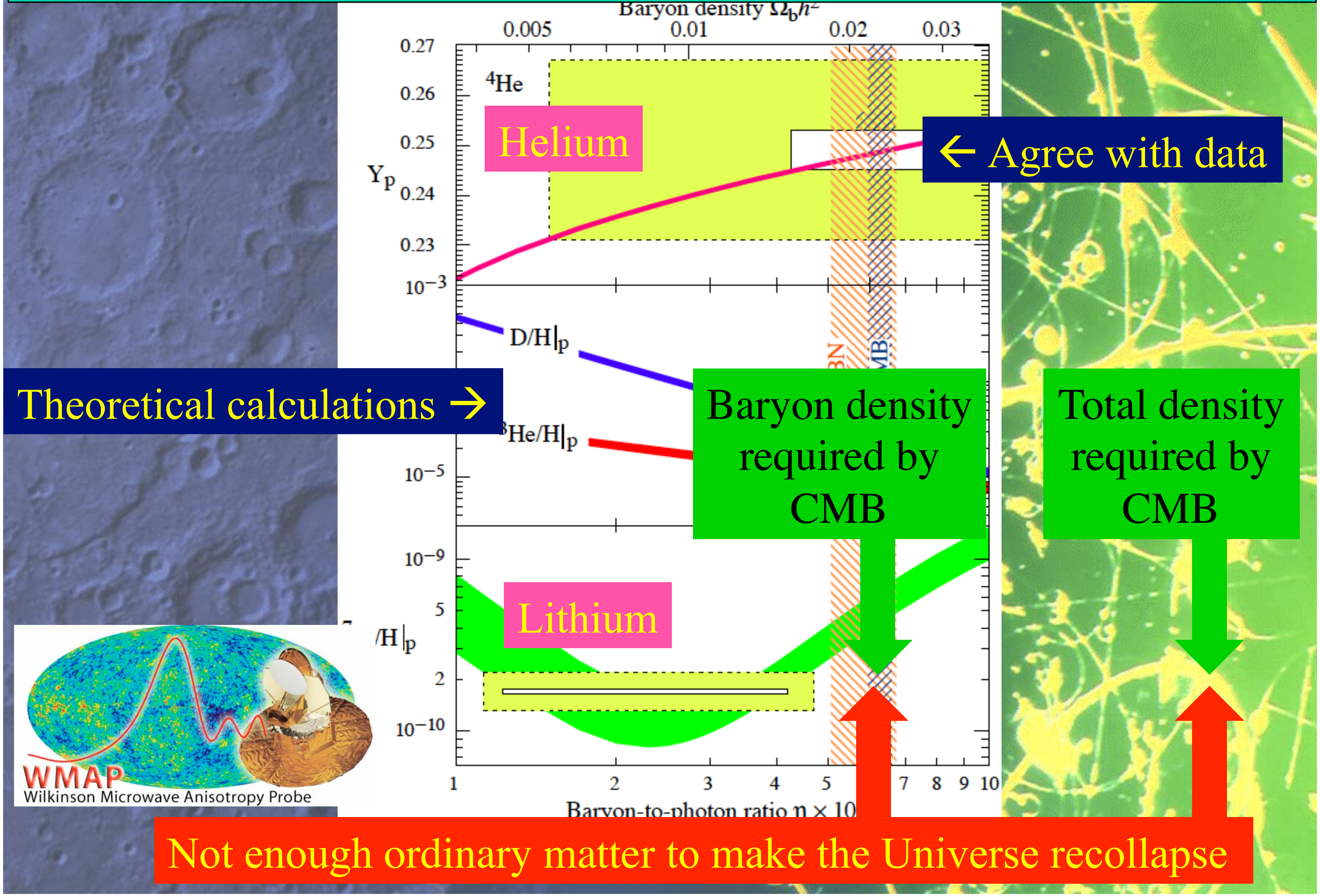


WMAP Constraints on Density



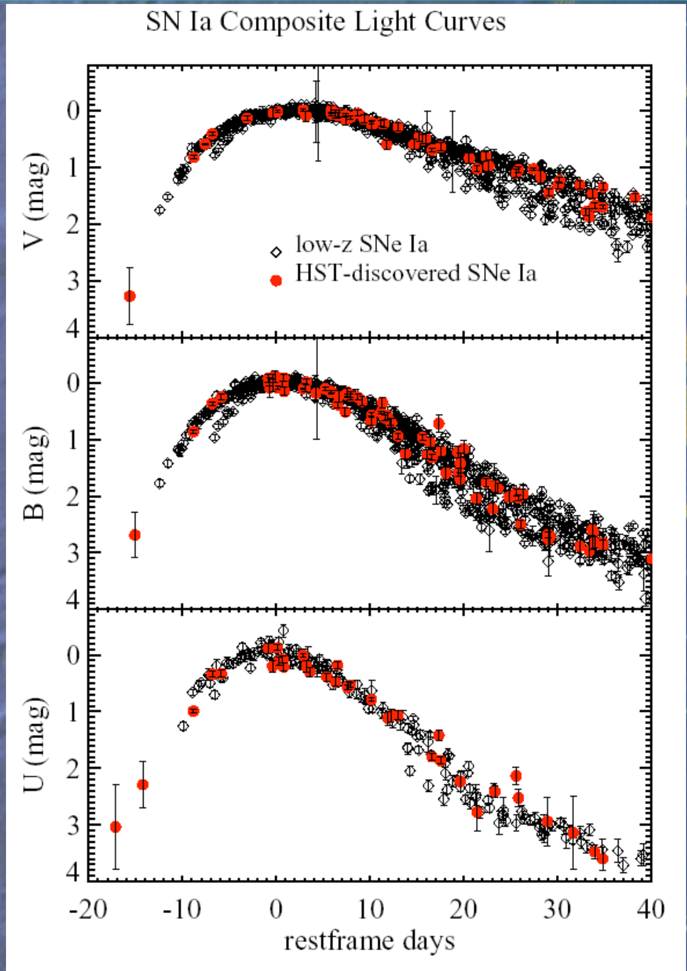


Abundances of light elements in the Universe

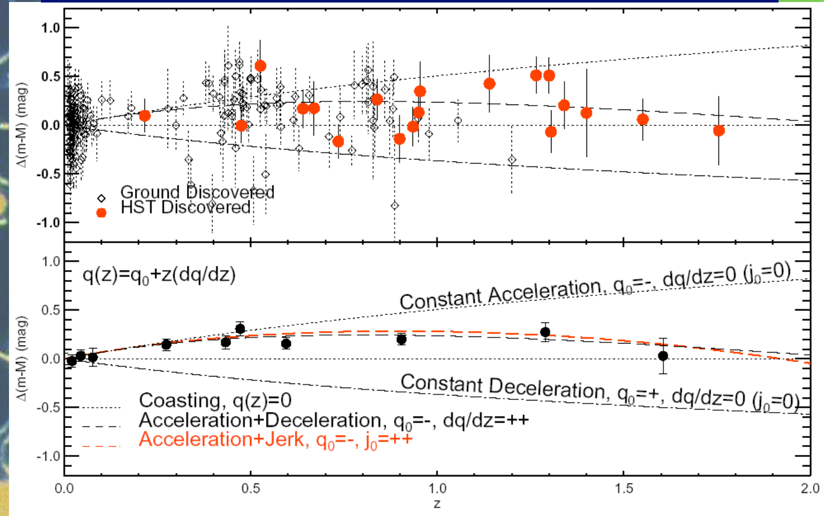


Direct evidence for dark energy

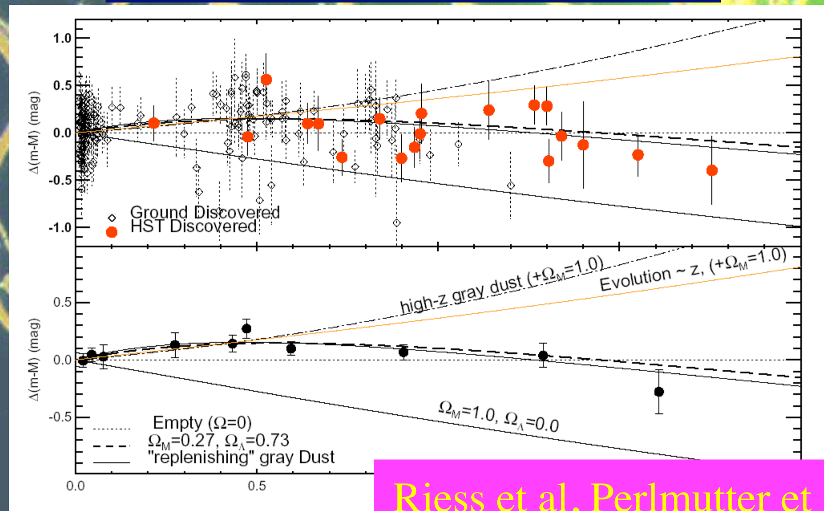
High-redshift supernovae are standard candles



Universe now accelerating, previously decelerating



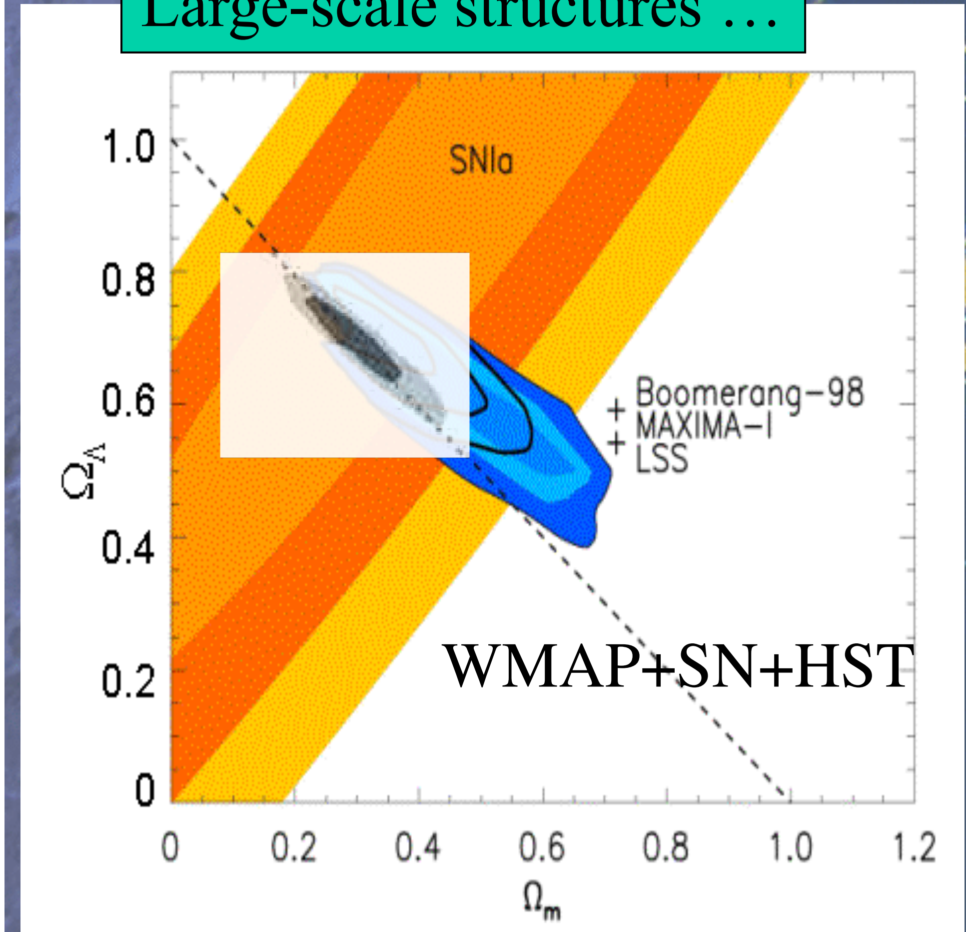
not dust, not evolution



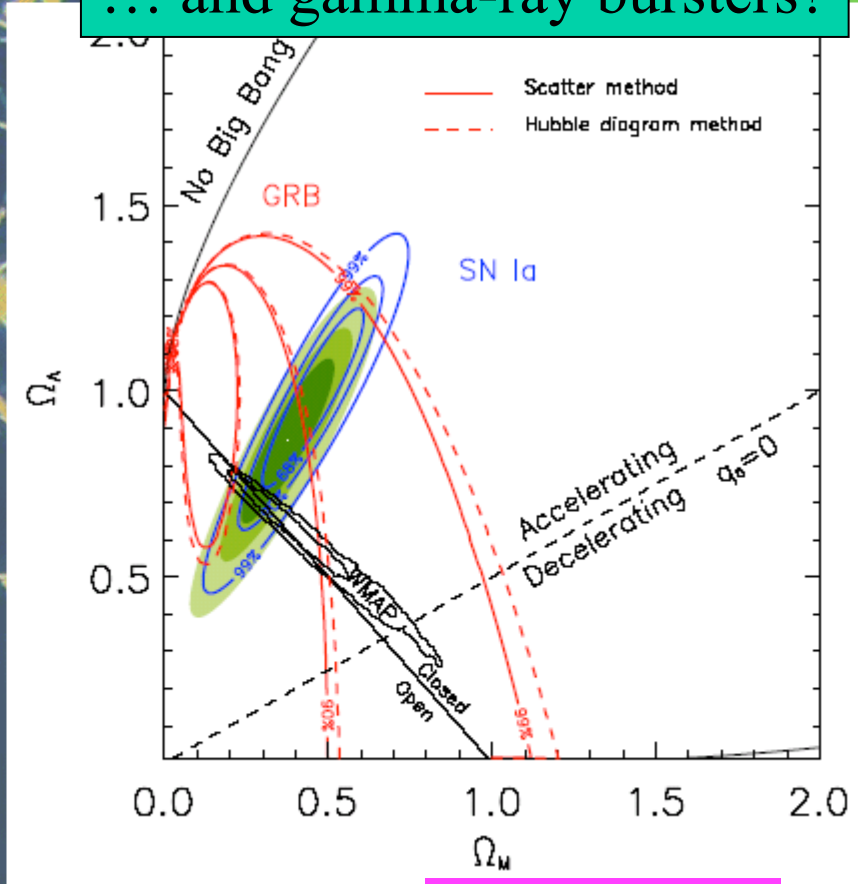
Riess et al, Perlmutter et al

Concordance Cosmological Model

WMAP, Supernovae, Large-scale structures …

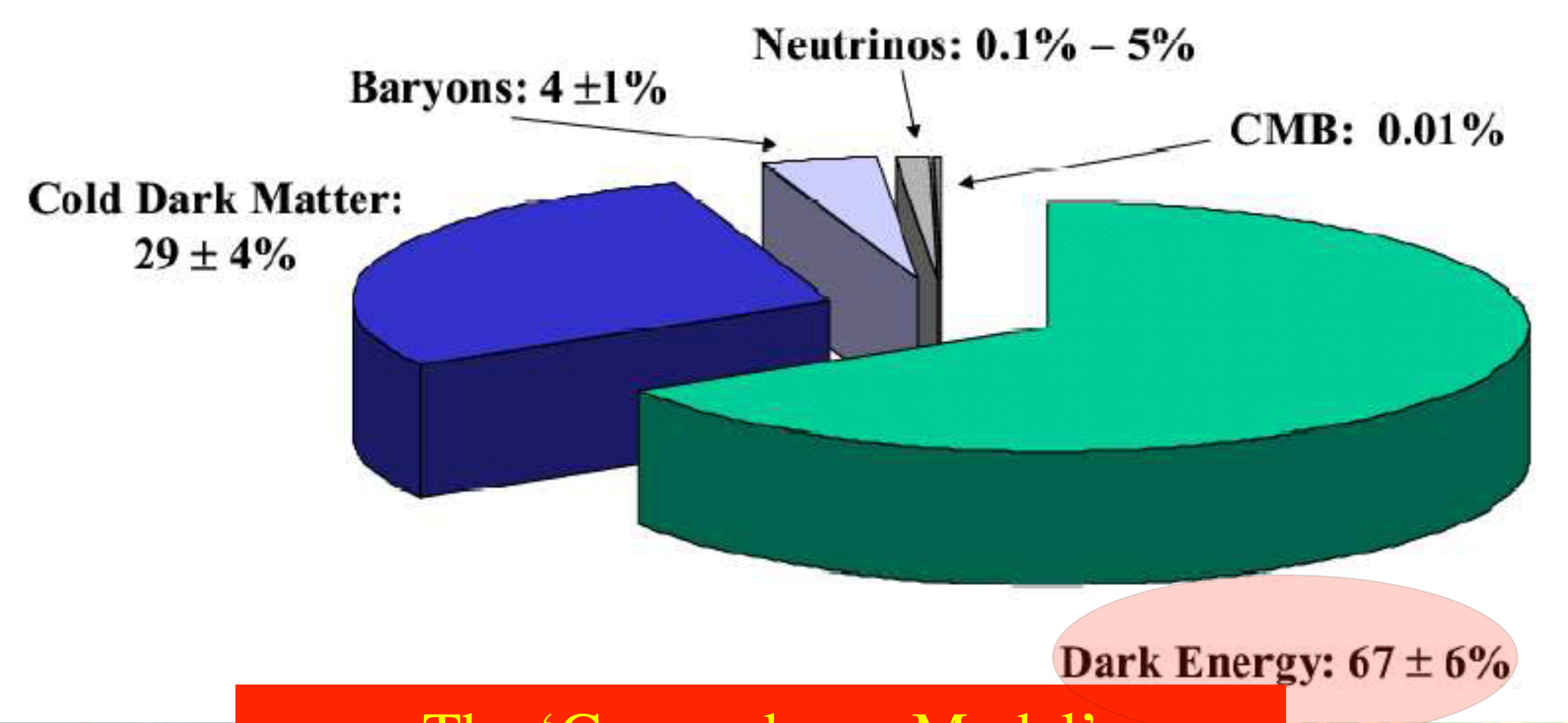


… and gamma-ray bursters?



Ghirlanda et al

A Strange Recipe for a Universe

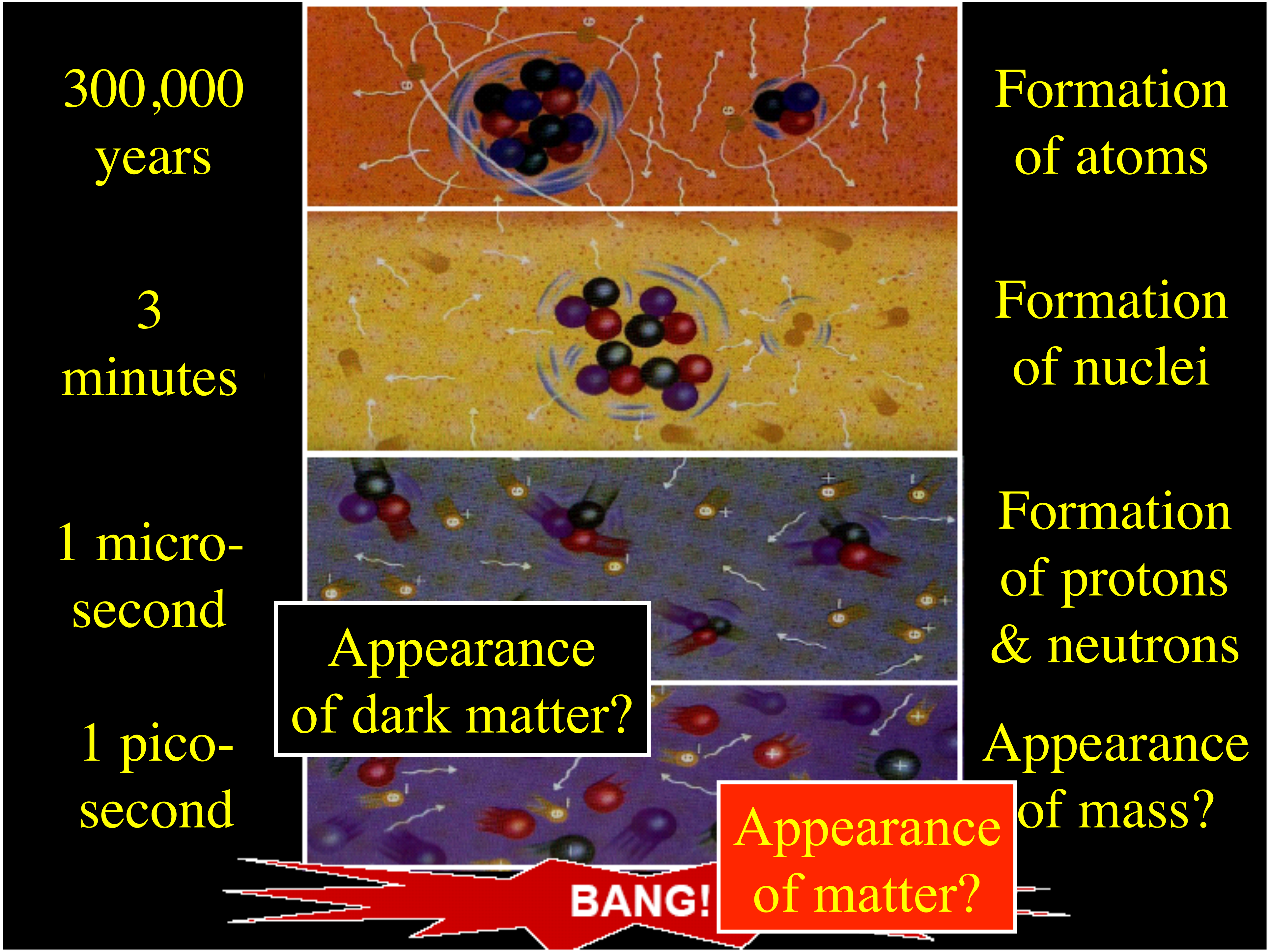


The 'Concordance Model'
prompted by astrophysics & cosmology

Open Cosmological Questions

- Where did the matter come from?
  - 1 proton for every 1,000,000,000 photons
- What is the dark matter?
  - Much more than the normal matter
- What is the dark energy?
  - Even more than the dark matter
- Why is the Universe so big and old?
  - Mechanism for cosmological inflation

Need particle physics to answer these questions


300,000 years
Formation of atoms
3 minutes
Formation of nuclei
1 micro-second
Formation of protons & neutrons
Appearance of dark matter?
1 pico-second
Appearance of mass?
BANG!
Appearance of matter?

The Very Early Universe

- Size: a → zero
- Age: t → zero
- Temperature: T → large

  $T \sim 1/a,\ t \sim 1/T^2$
- Energies: $E \sim T$
- Rough magnitudes:

  T ~ 10,000,000,000 degrees

  E ~ 1 MeV ~ mass of electron

  t ~ 1 second

Need particle physics to describe earlier history

Mathematical Description

- Large-scale universe ~ isotropic & homogeneous
- Only possible form of metric (Robertson-Walker)

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

- Redshift: $z \equiv \frac{\nu_1 - \nu_2}{\nu_2} \simeq \frac{v_{12}}{c}$
- Related to expansion rate:

$$\frac{v_{12}}{c} = \dot{R}\,\delta r = \frac{\dot{R}}{R}\delta t = \frac{\delta R}{R} = \frac{R_2 - R_1}{R_1} \qquad 1 + z = \frac{\nu_1}{\nu_2} = \frac{R_2}{R_1}$$

- **No Einstein yet!**

General-Relativistic Description

- Einstein's equations:

$$\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}$$

  - Cosmological constant Λ part of $T_{\mu\nu}$

- Treat matter & radiation as fluid:

$$T_{\mu\nu} = -p g_{\mu\nu} + (p + \rho) u_\mu u_\nu \qquad \dot{\rho} = -3H(\rho + p)$$

- Friedman-Lemaître equations:

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \qquad \frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3} (\rho + 3p)$$

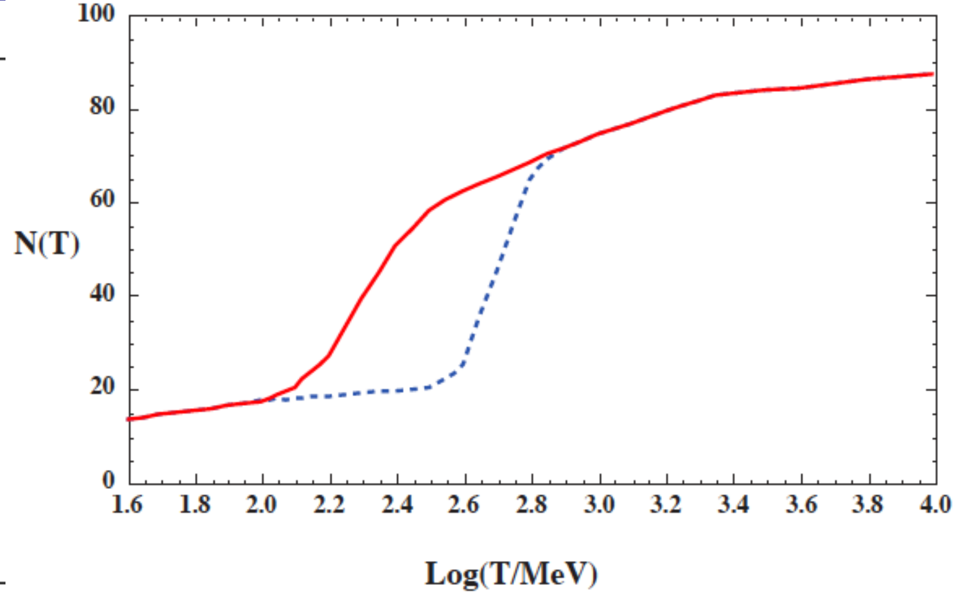
Relativistic Particles

- Relativistic degrees of freedom:

$$\rho = \left(\sum_B g_B + \frac{7}{8}\sum_F g_F\right)\frac{\pi^2}{30}T^4 \equiv \frac{\pi^2}{30}N(T)T^4$$

- Degrees of freedom in Standard Model:
- Expansion rate: $R(t) \propto t^{1/2}\ ; \qquad H = 1/2t$

Temperature	New Particles	$4N(T)$
$T < m_e$	γ's + ν's	29
$m_e < T < m_\mu$	$e^\pm$	43
$m_\mu < T < m_\pi$	$\mu^\pm$	57
$m_\pi < T < T_c{}^\dagger$	π's	69
$T_c < T < m_{\rm strange}$	π's + $u, \bar{u}, d, \bar{d}$ + gluons	205
$m_s < T < m_{\rm charm}$	$s, \bar{s}$	247
$m_c < T < m_\tau$	$c, \bar{c}$	289
$m_\tau < T < m_{\rm bottom}$	$\tau^\pm$	303
$m_b < T < m_{\rm W,Z}$	$b, \bar{b}$	345
$m_{W,Z} < T < m_{\rm Higgs}$	$W^\pm, Z$	381
$m_H < T < m_{\rm top}$	H^0	385
$m_t < T$	$t, \bar{t}$	427



How Flat is the Universe?

- Measure density relative to critical value:

$$\Omega_{\text{tot}} = \rho/\rho_c$$

- Curvature: $k/R^2 = H^2(\Omega_{\text{tot}} - 1)$

  where critical density $\rho_c \equiv \frac{3H^2}{8\pi G_N} = 1.88 \times 10^{-26}\, h^2 \text{ kg m}^{-3} = 1.05 \times 10^{-5}\, h^2 \text{ GeV cm}^{-3}$

- And Hubble expansion rate: $H \equiv 100\, h \text{ km s}^{-1} \text{ Mpc}^{-1}$
- Exponential expansion if Λ dominates:

$$R(t) \propto e^{\sqrt{\Lambda/3}t}$$

Age of the Universe

- Integrating Hubble expansion rate:

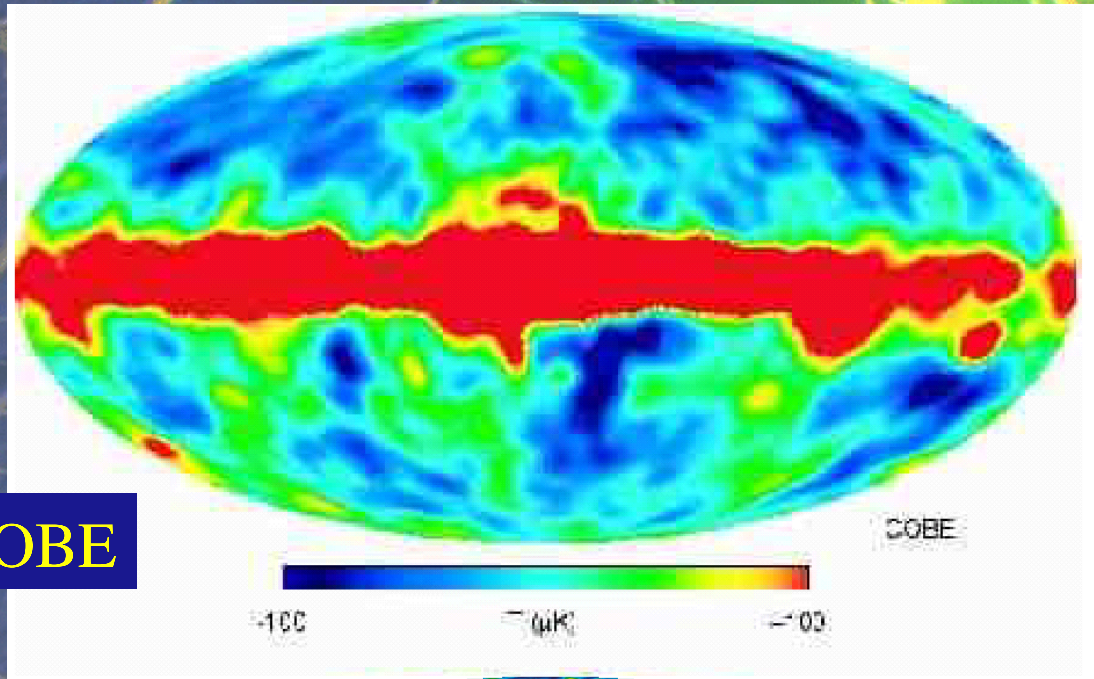
$$H_0 t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)}$$
$$= \int_0^\infty \frac{dz}{(1+z)\left[(1+z)^2(1+\Omega_m z) - z(2+z)\Omega_v\right]^{1/2}}$$

- Approximate solution:

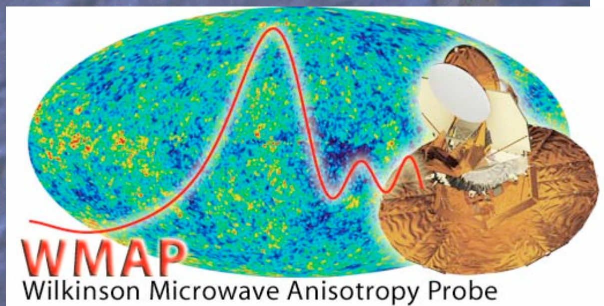
$$H_0 t_0 \simeq \frac{2}{3}\left(0.7\Omega_m + 0.3 - 0.3\Omega_v\right)^{-0.3}$$

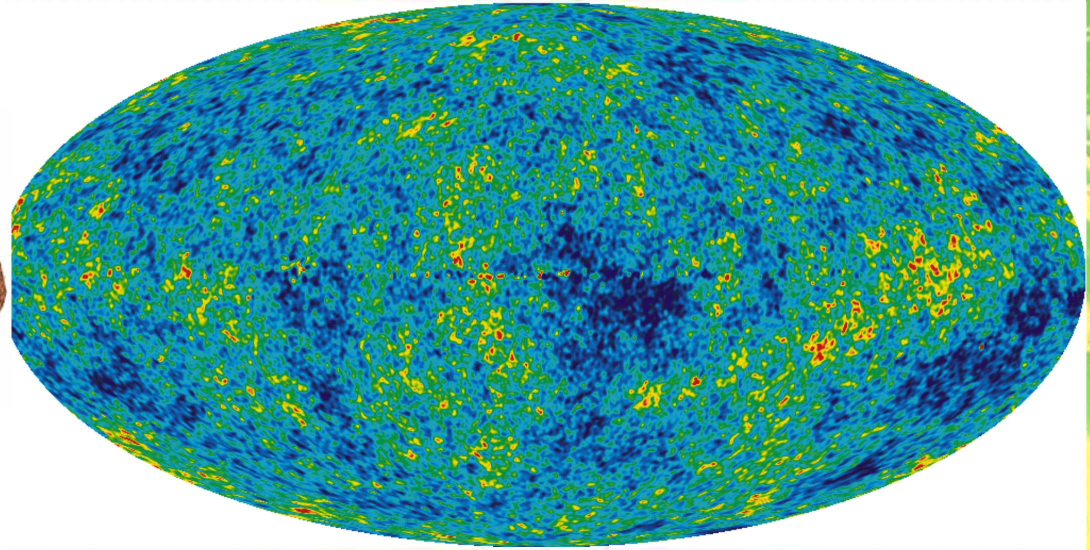
- Estimated age: **13.7 billion years**

The Cosmic Microwave Background



According to COBE

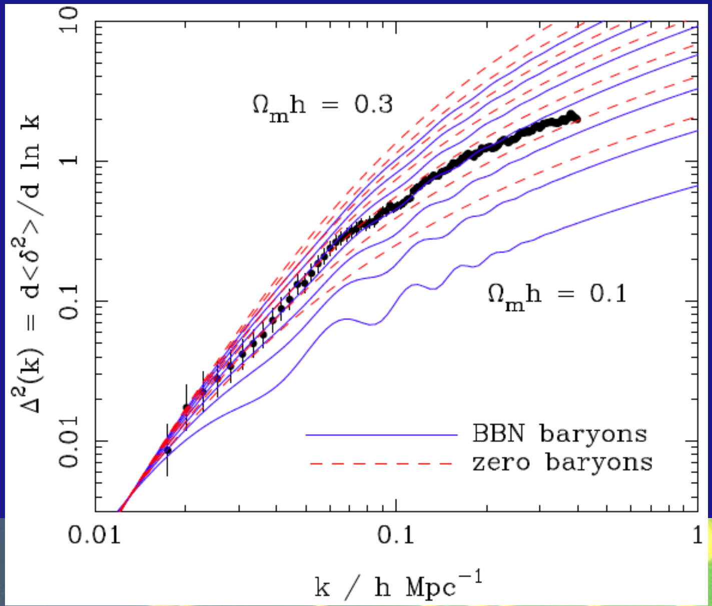




What is the origin of the fluctuations in the CMB?

Density Perturbations

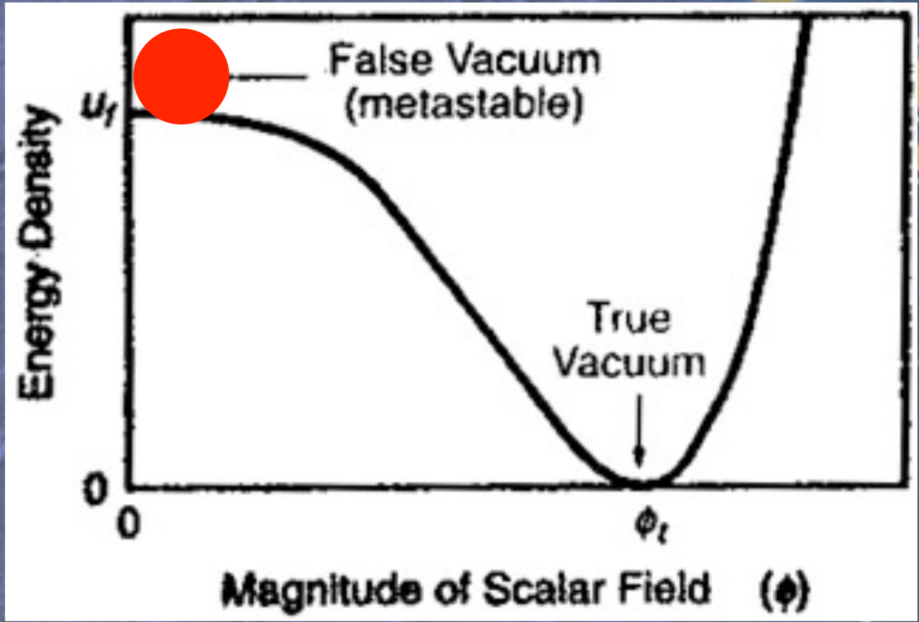
- Generated by quantum fluctuations in inflaton field
- Density perturbations: $\delta(\mathbf{x}) \equiv \frac{\rho(\mathbf{x}) - \langle\rho\rangle}{\langle\rho\rangle}$ $\delta(\mathbf{x}) = \sum \delta_{\mathbf{k}} e^{-i\mathbf{k}\cdot\mathbf{x}}$
- Power spectrum: $\langle\delta^2\rangle = \sum |\delta_{\mathbf{k}}|^2 \equiv \sum P(k)$
- Evolution depends on equation of state
- Measured in CMB, galaxy distributions

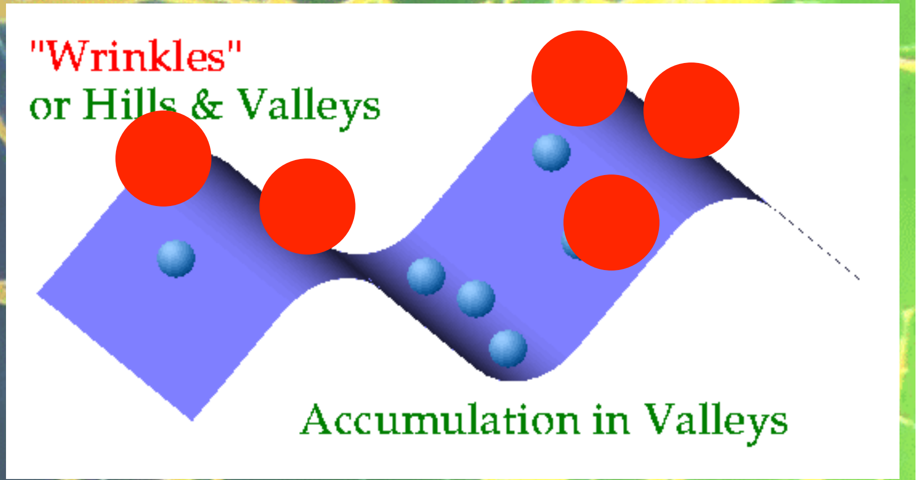


Origin of Structures in Universe

Small primordial fluctuations:
one part in 10^5

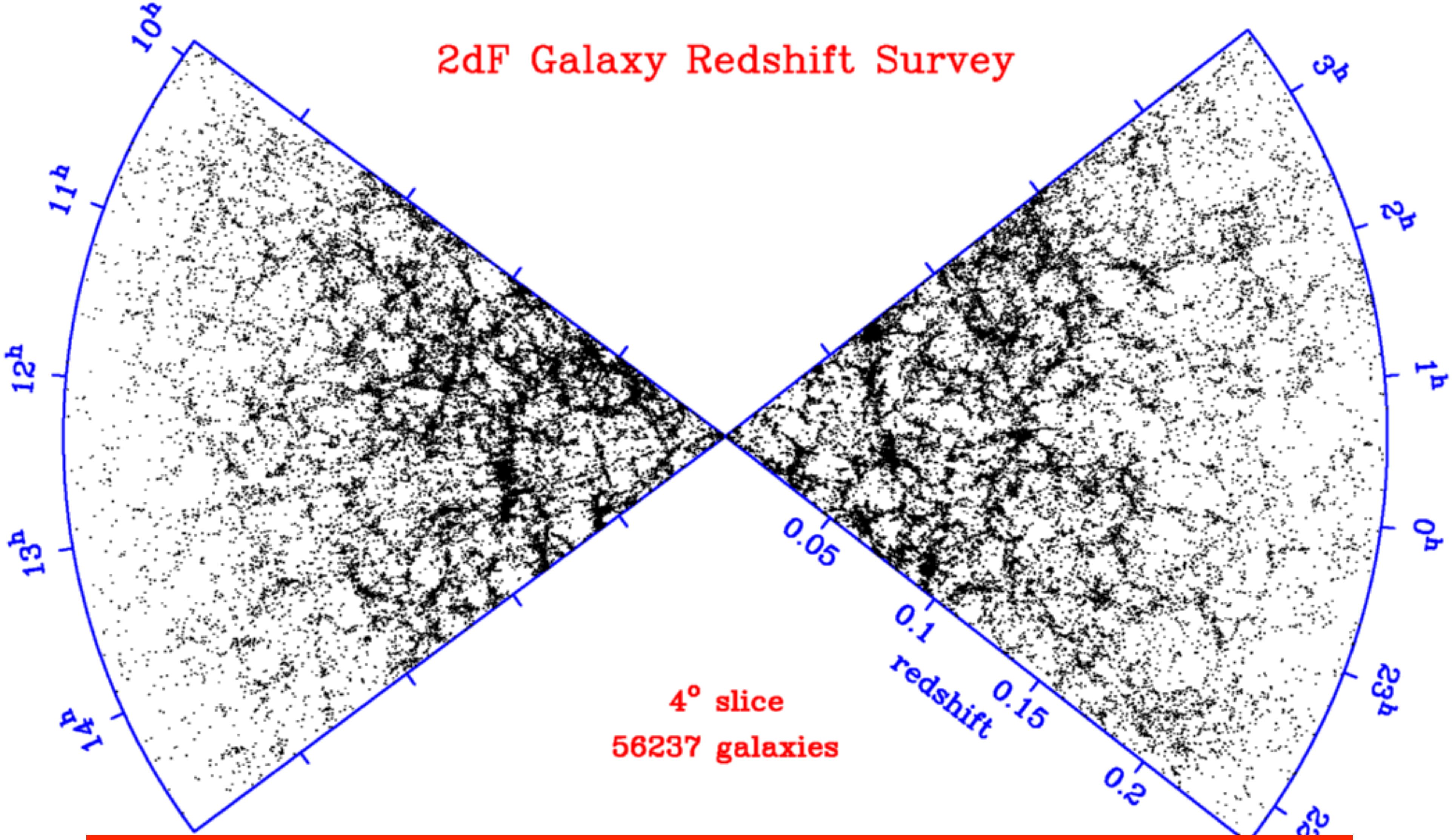
Gravitational instability:
Matter falls into
the overdense regions





Convert into matter with varying density

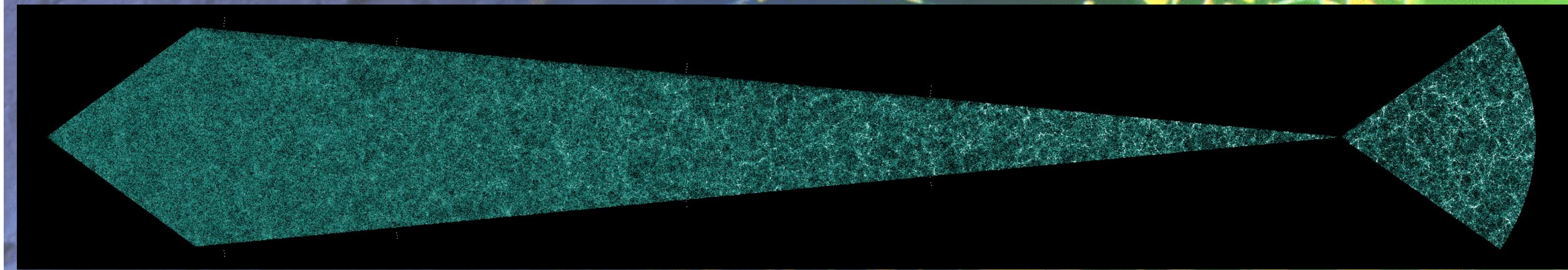
Structures observed in the Universe



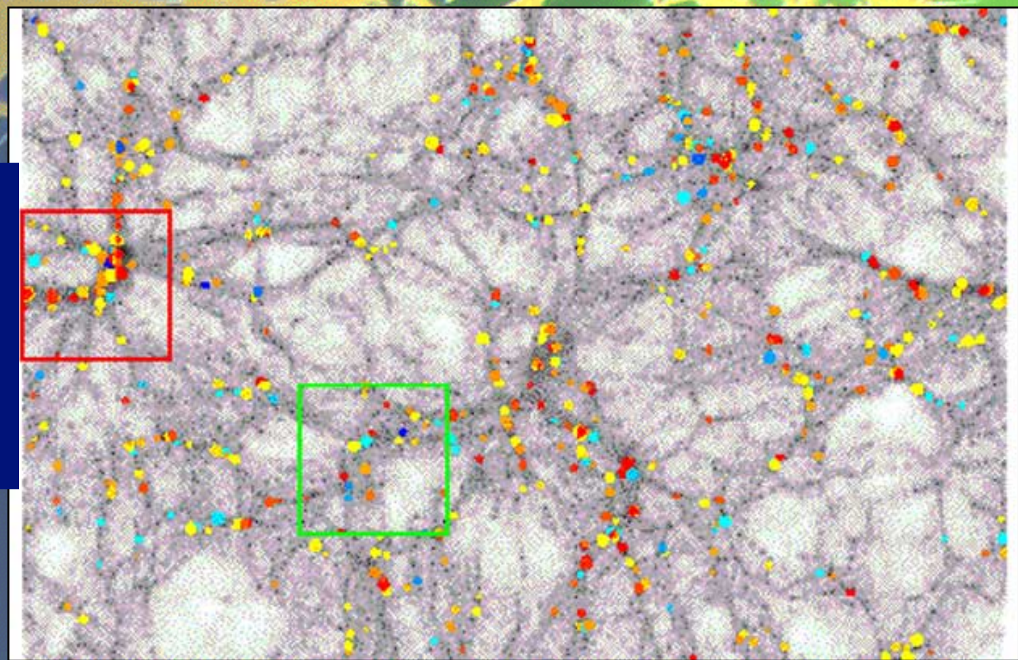
Galaxies → Clusters → smooth at largest scales

Simulation of Cold Dark Matter

Initially quite homogeneous: gravity → structures form → today



Simulation of present-day Universe:
- Filaments of dark matter,
- Clusters of galaxies at nodes



Structures in Universe vs Concordance Model

Flat Universe:

$\Omega_{Tot} = 1$,

Cold dark matter:

$\Omega_{CDM} \sim 0.25$,

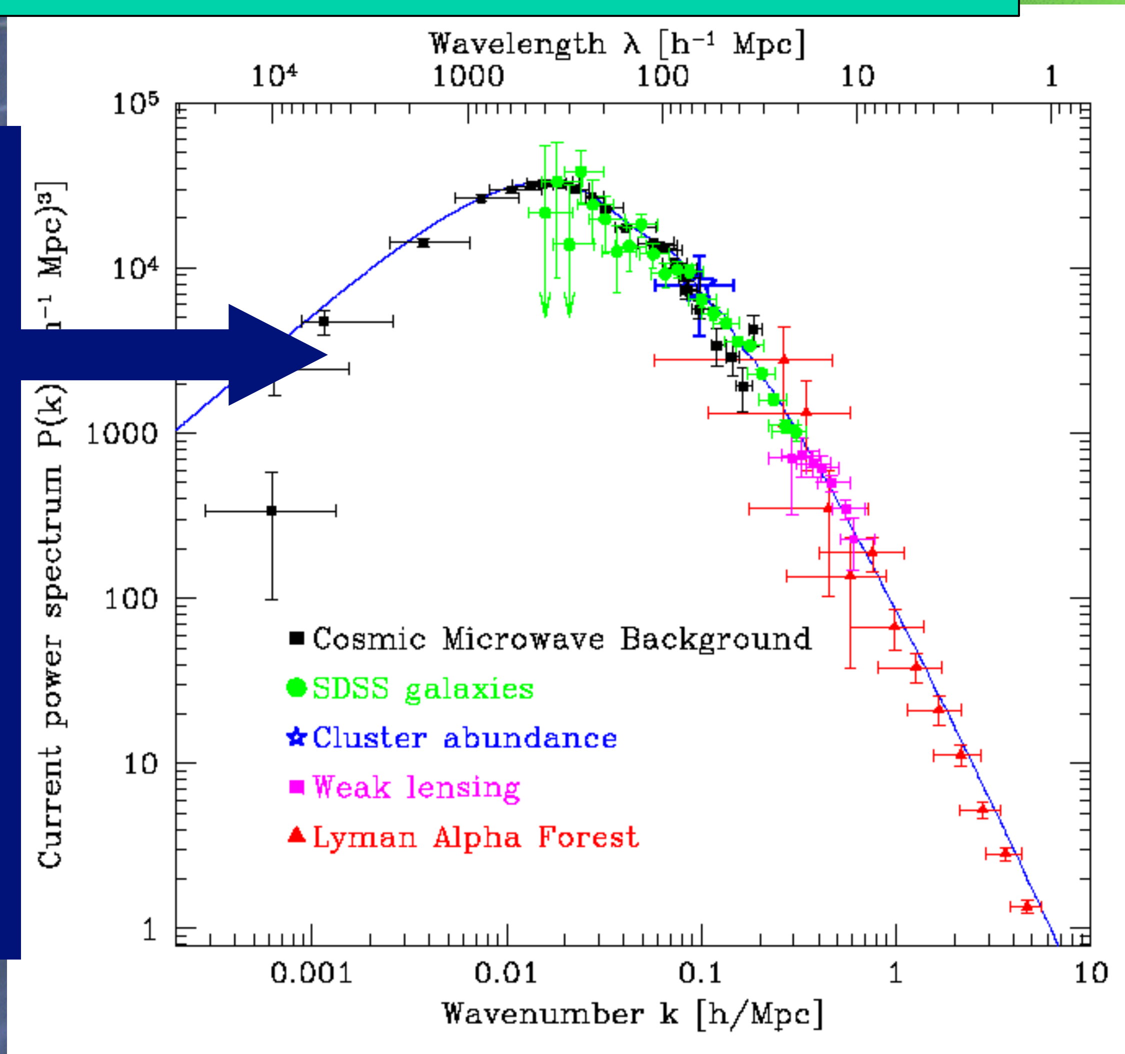
No hot dark matter,

Few baryons:

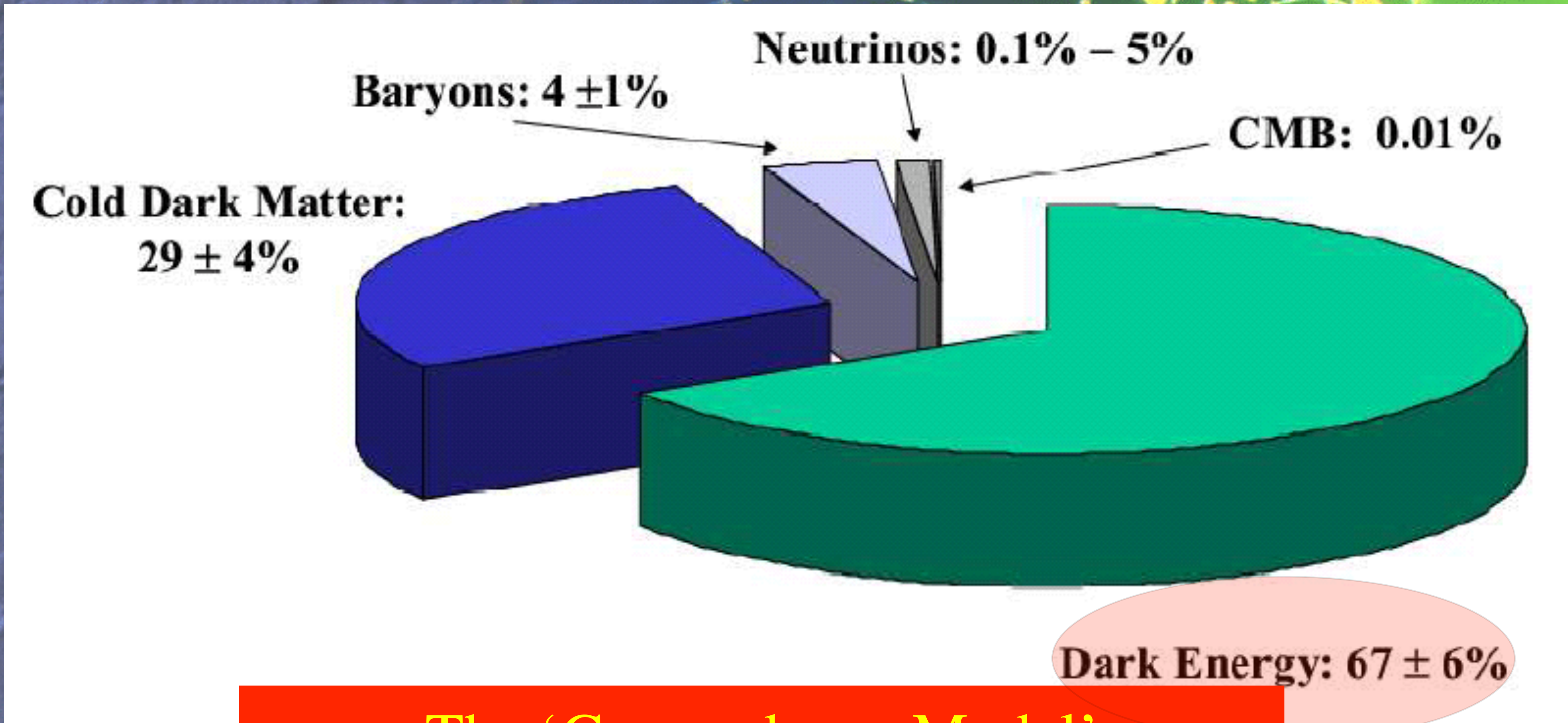
$\Omega_b \sim 0.05$,

Dark energy:

$\Omega_\Lambda \sim 0.7$

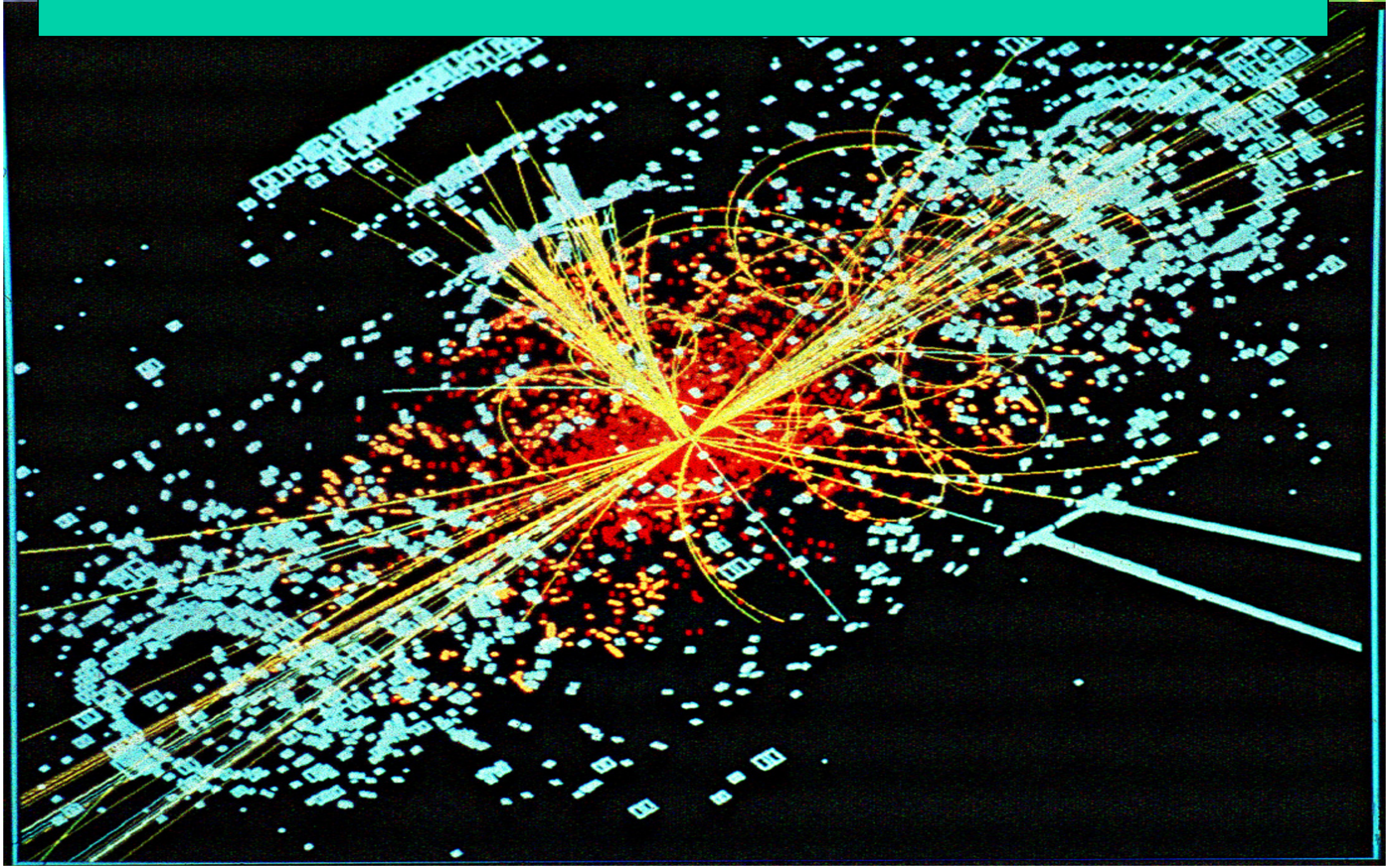


A Strange Recipe for a Universe



The 'Concordance Model'
prompted by astrophysics & cosmology

Simulated Production of a Higgs Boson



The Higgs Boson and Cosmology

- Changed the state of the Universe when it was about 10^{-12} seconds old
- May have generated then the matter in the Universe
- Contributes (too much) to today's dark energy
- A related inflaton might have expanded the Universe when it was about 10^{-35} seconds old

Scalar Fields & Inflation

- Energy-momentum tensor for scalar field:

$$T_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - \frac{1}{2}g_{\mu\nu}\partial_\rho\phi\partial^\rho\phi - g_{\mu\nu}V(\phi)$$

- Density & pressure:

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}R^{-2}(t)(\nabla\phi)^2 + V(\phi)$$

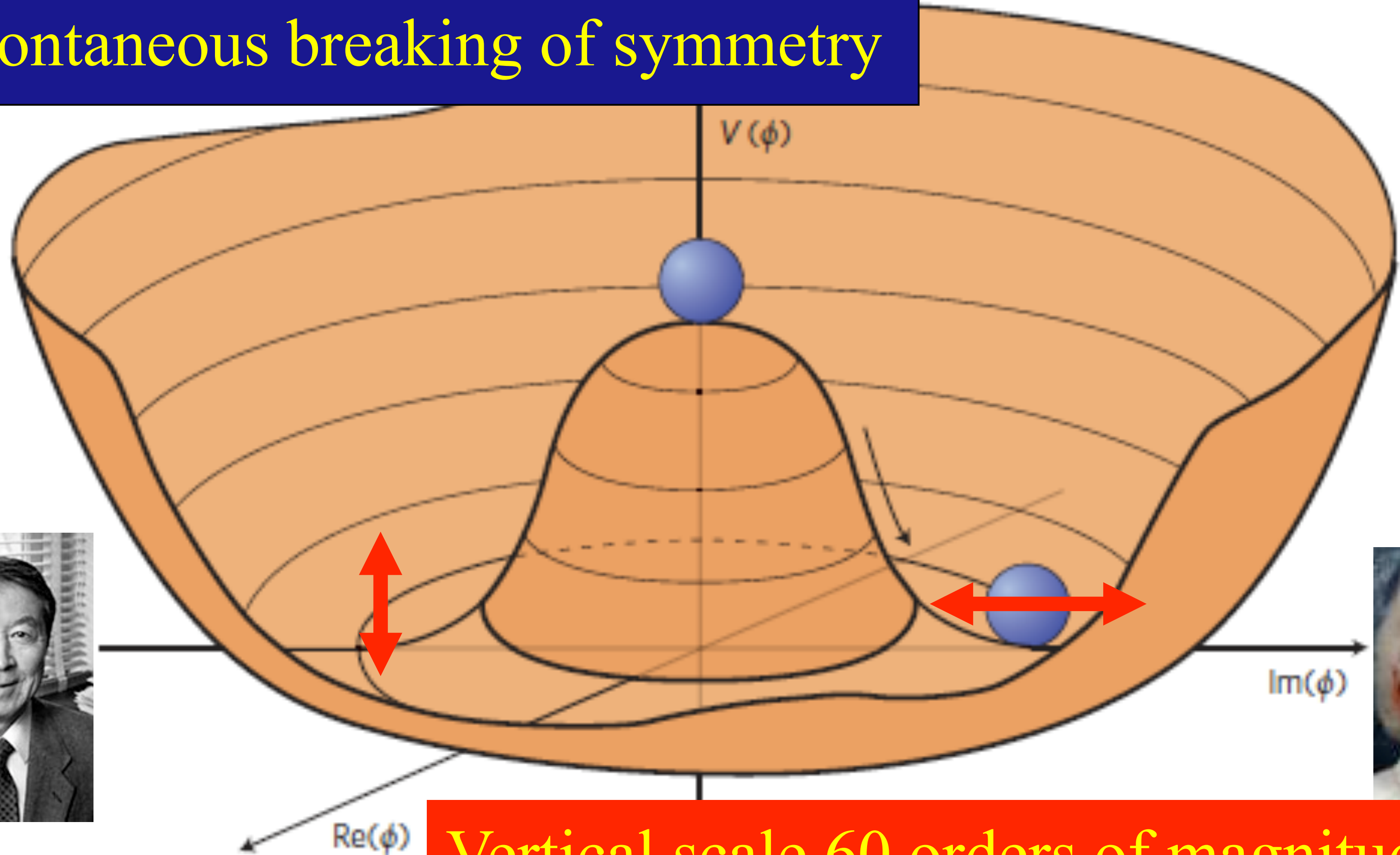
$$p = \frac{1}{2}\dot{\phi}^2 - \frac{1}{6}R^{-2}(t)(\nabla\phi)^2 - V(\phi)\ ,$$

- Evolution of scalar field: $\ddot{\phi} + 3H\dot{\phi} = -\partial V/\partial\phi$
- Slow-roll parameters: $\epsilon \equiv \frac{M_{\rm P}^2}{16\pi}(\frac{V'}{V})^2 \qquad \eta \equiv \frac{M_{\rm P}^2}{8\pi}(\frac{V''}{V})$
- If these are small, near-exponential expansion:

$$R(t) \propto e^{\sqrt{\Lambda/3}t}$$: $\Lambda = V(\phi)$

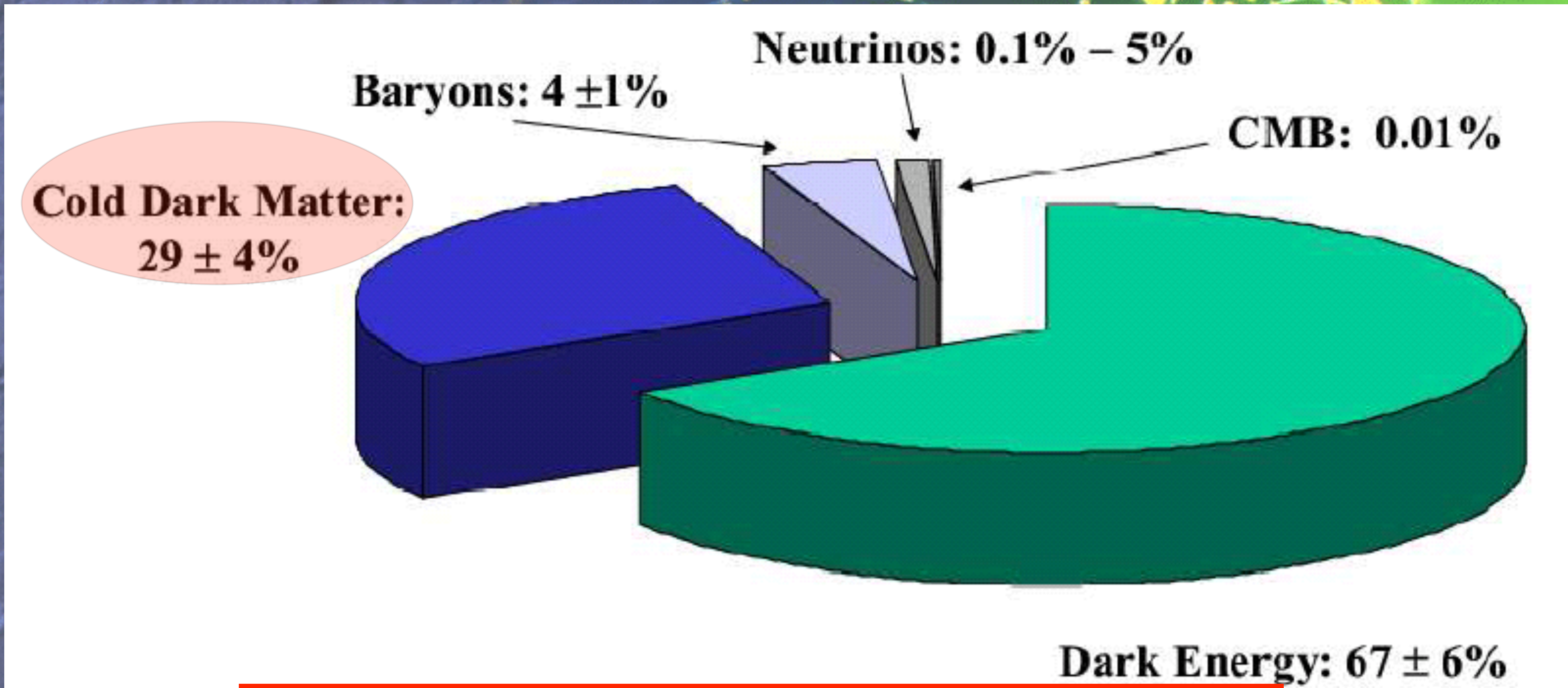
Nambu and Higgs

Spontaneous breaking of symmetry



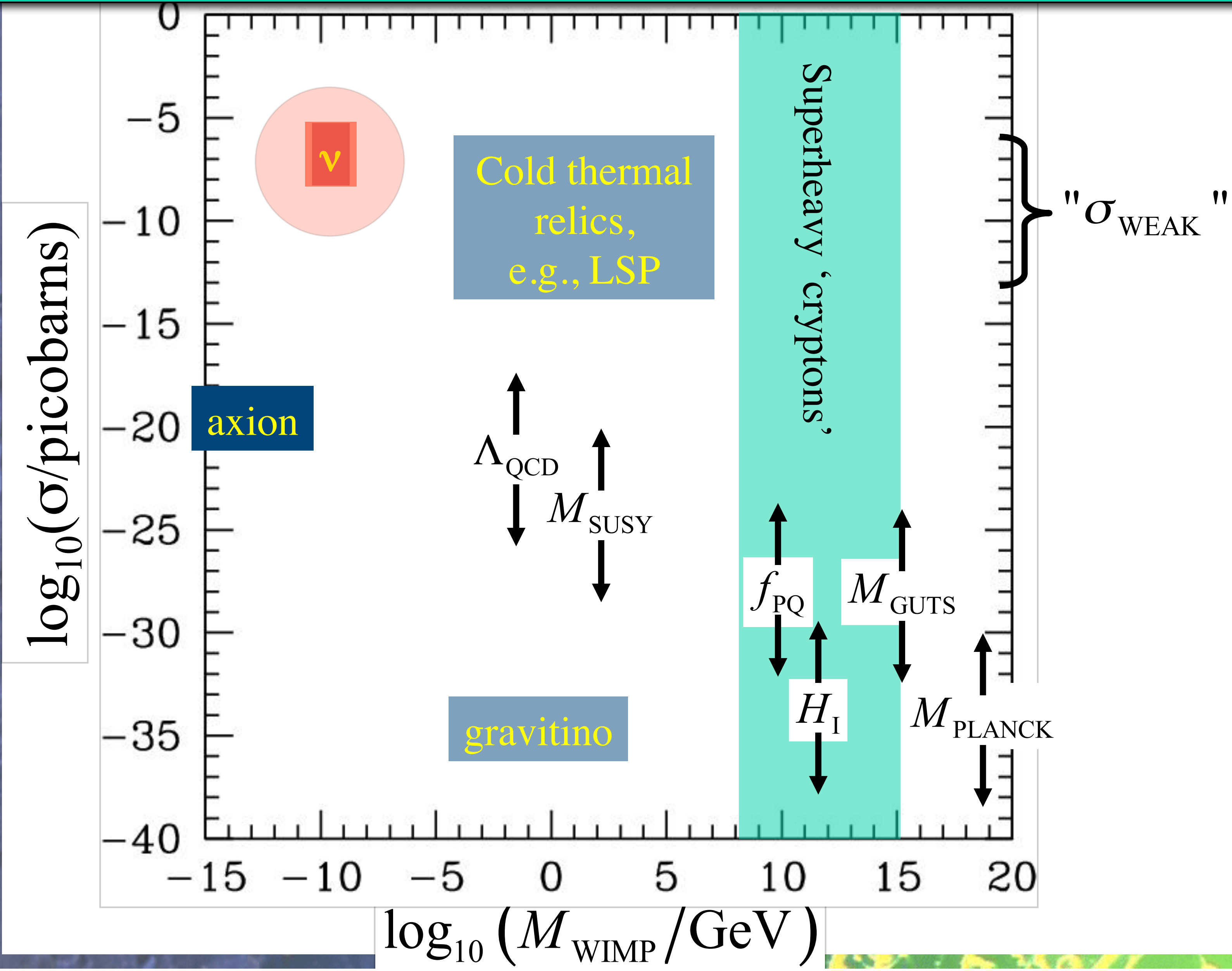
Vertical scale 60 orders of magnitude greater than measured dark energy

A Strange Recipe for a Universe



The 'Concordance Model'
prompted by astrophysics & cosmology

Particle Dark Matter Candidates



Do Neutrinos matter?

- **They exist!**
- And have very small masses

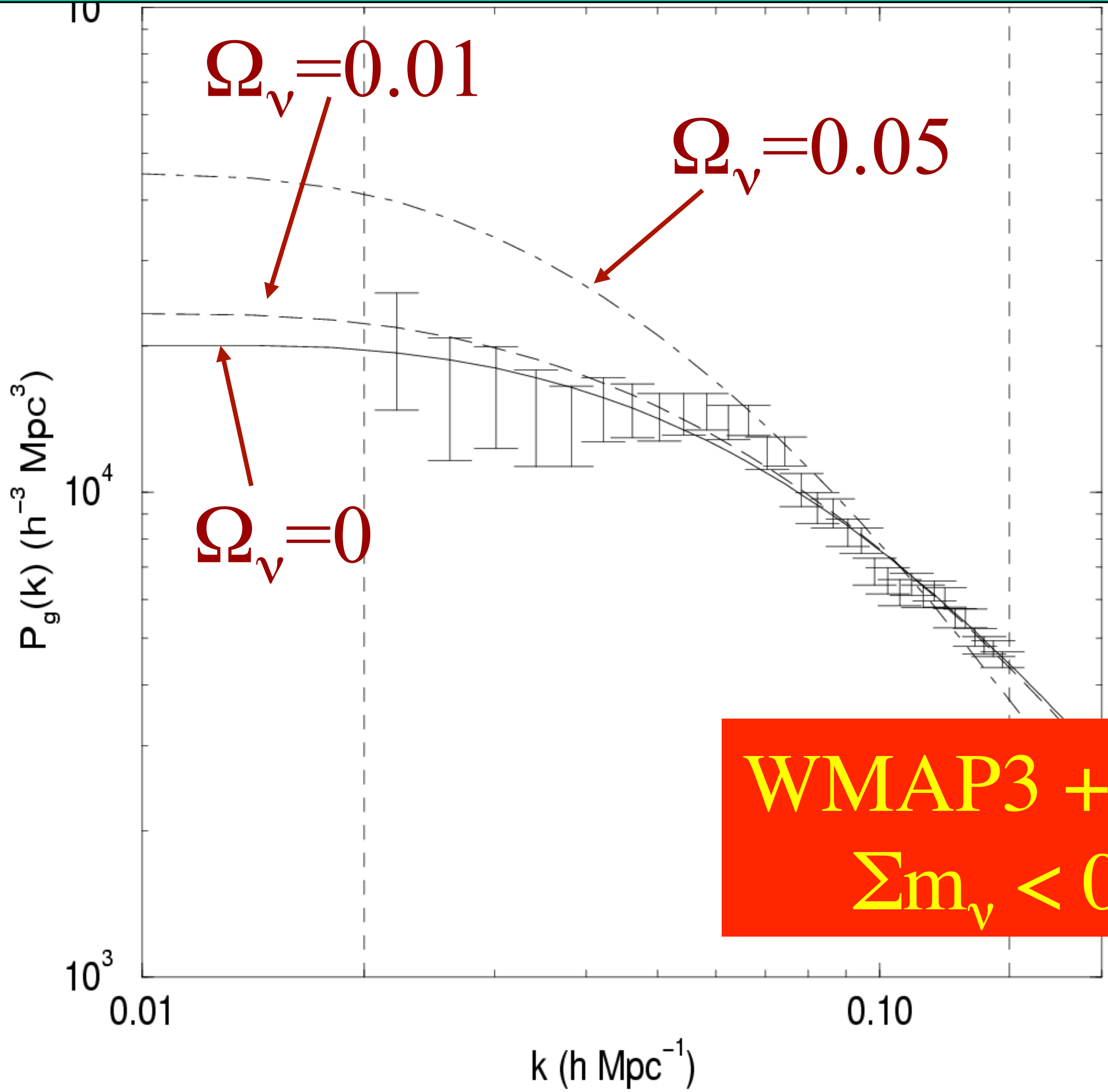
  but non-zero – oscillation experiments
- Might make up some of dark matter

  less than 10%?
- But would escape from galaxies

  moving relativistically
- Need heavier stable dark matter particles

  supersymmetric particles?

Not much neutrino mass density



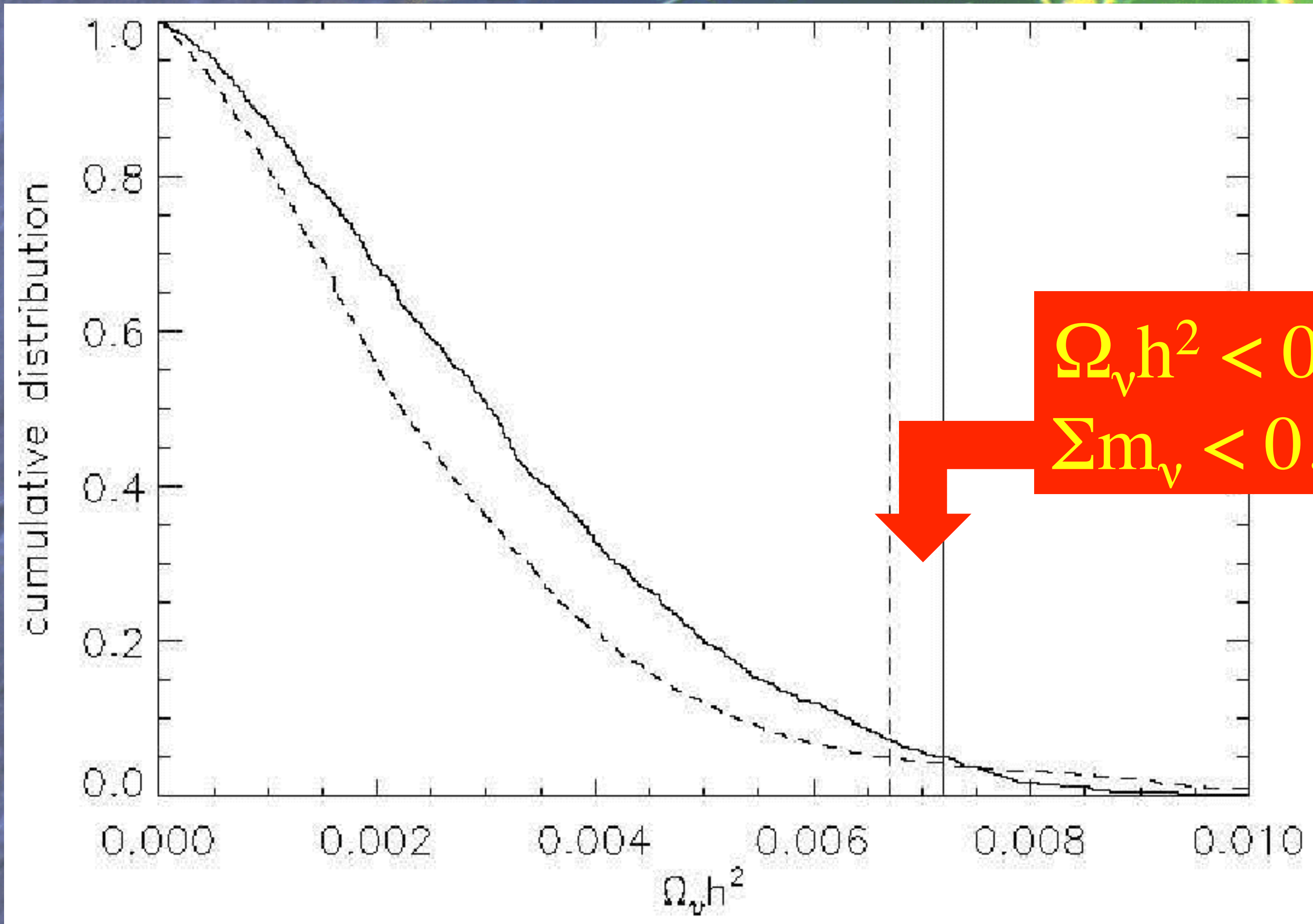
m: astro-ph/0204152

WMAP3 + Lyman α:
Σm_ν < 0.17 eV

Data on large-scale structures

According to WMAP et al …

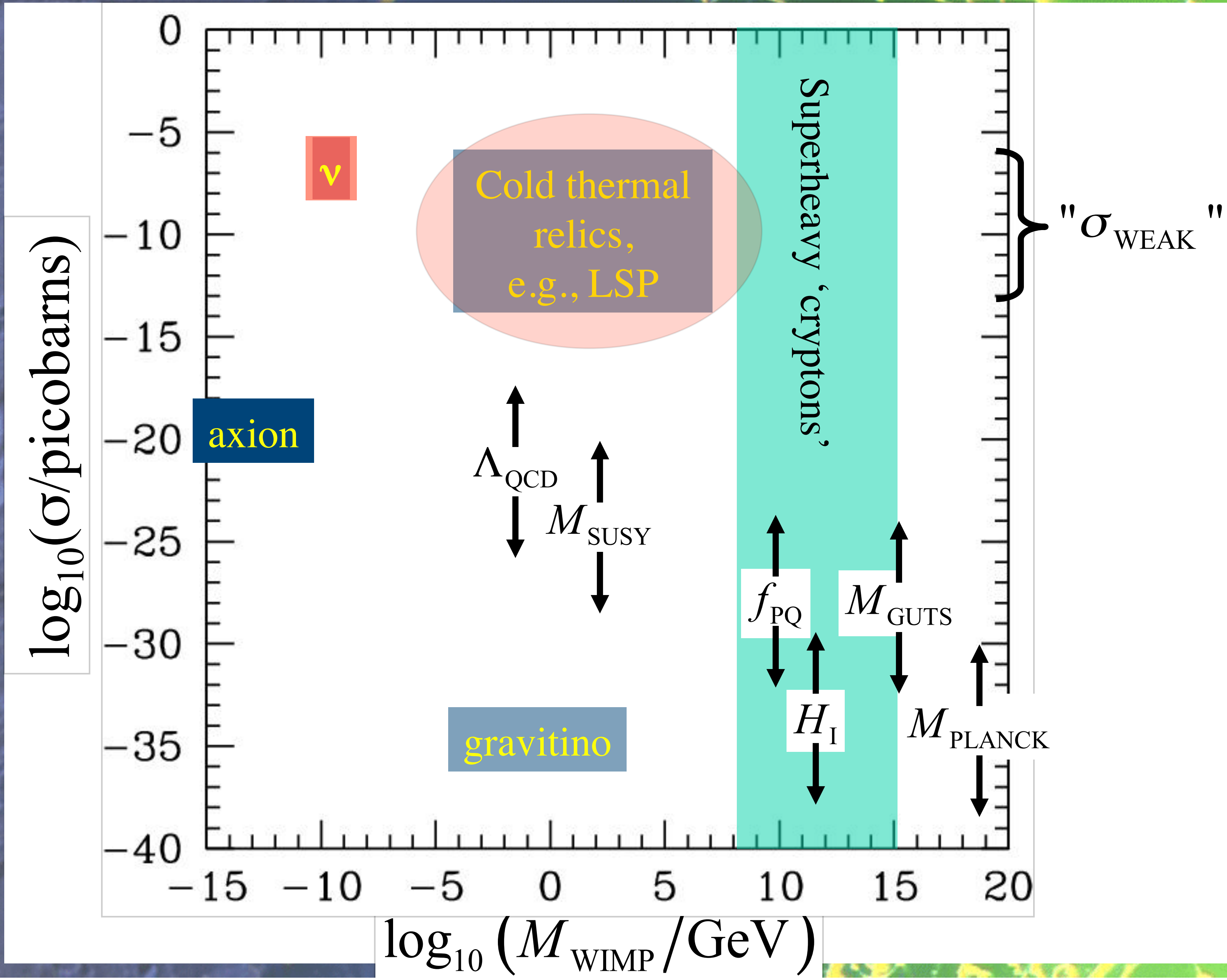
Not much Hot (Neutrino) Dark Matter



$\Omega_\nu h^2 < 0.007$

$\Sigma m_\nu < 0.17$ eV

Particle Dark Matter Candidates



Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates

  0 - ½ - 1 - 3/2 - 2

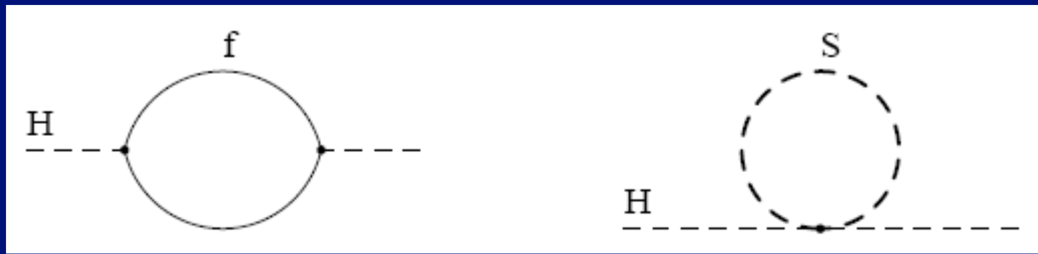
  Higgs - Electron - Photon - Gravitino – Graviton
- Many phenomenological motivations
  - Would help fix particle masses
  - Would help unify forces
  - Predicts light Higgs boson
  - Could fix discrepancy in g_μ - 2
- **Could provide dark matter for the astrophysicists and cosmologists**

Why Supersymmetry (Susy)?

- Hierarchy problem: why is $m_W \ll m_P$?
  ($m_P \sim 10^{19}$ GeV is scale of gravity)
- Alternatively, why is
  $G_F = 1/\, m_W^2 \gg G_N = 1/m_P^2$?
- Or, why is
  $V_{Coulomb} \gg V_{Newton}$? $e^2 \gg G\, m^2 = m^2 / m_P^2$
- Set by hand? What about loop corrections?
  $\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$
- Cancel boson loops ⇔ fermions
- Need $|\, m_B^2 - m_F^2| < 1\ \text{TeV}^2$

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

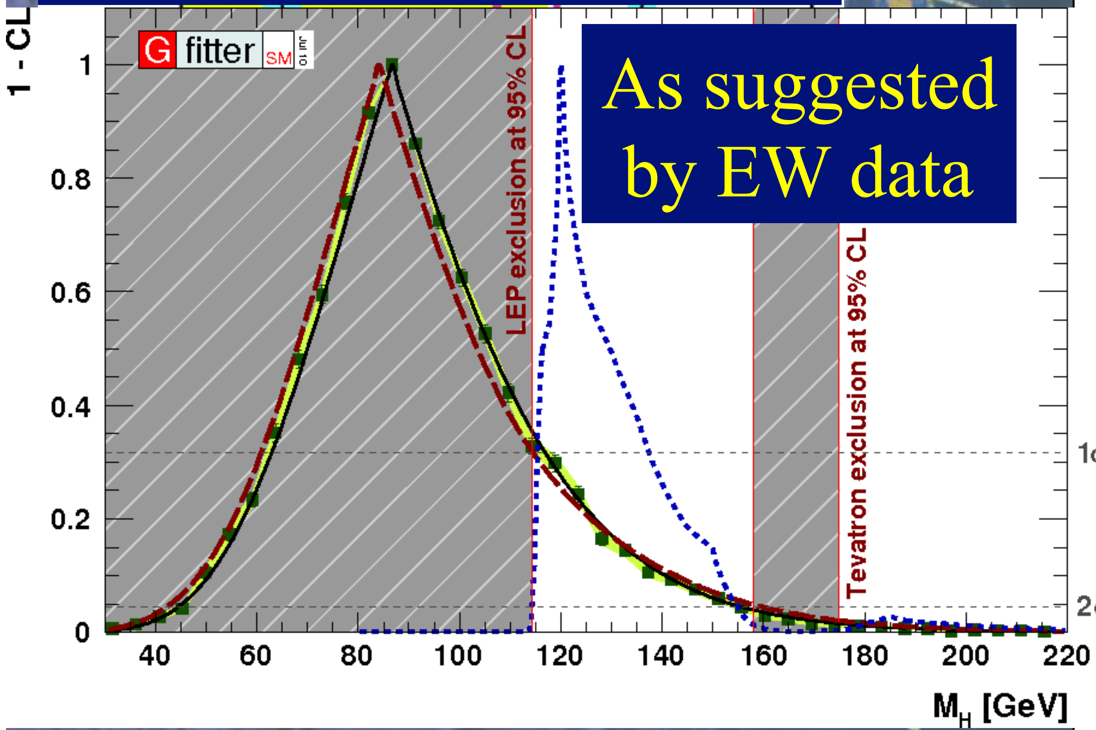
- Leading divergence cancelled if

$\lambda_S = y_f^2$ x 2 **Supersymmetry!**

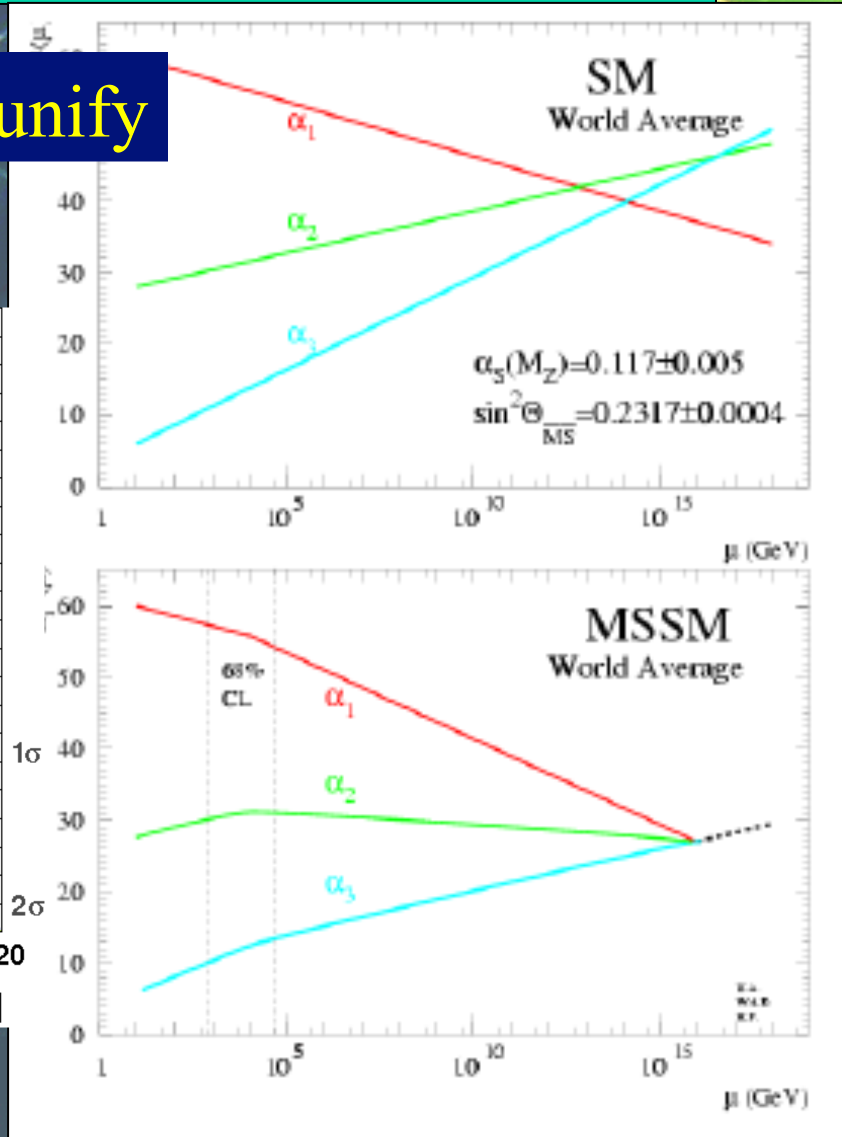
Other Reasons to like Susy

It enables the gauge couplings to unify

It predicts $m_H < 150$ GeV



As suggested by EW data



Minimal Supersymmetric Extension of Standard Model (MSSM)

- Double up the known particles:

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles

- Lightest supersymmetric particle (LSP) stable

Fayet

Possible Nature of LSP

- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ (partner of Z, H, γ)
  - Gravitino
    - (nightmare for astrophysical detection)

Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

  selectron, chargino > 100 GeV

  squarks, gluino > 400 GeV

- Indirect constraints

  Higgs > 114 GeV, b -> s γ

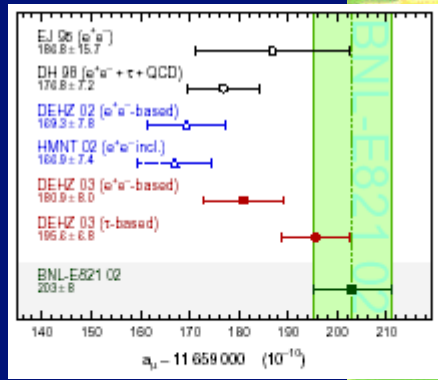
- Density of dark matter

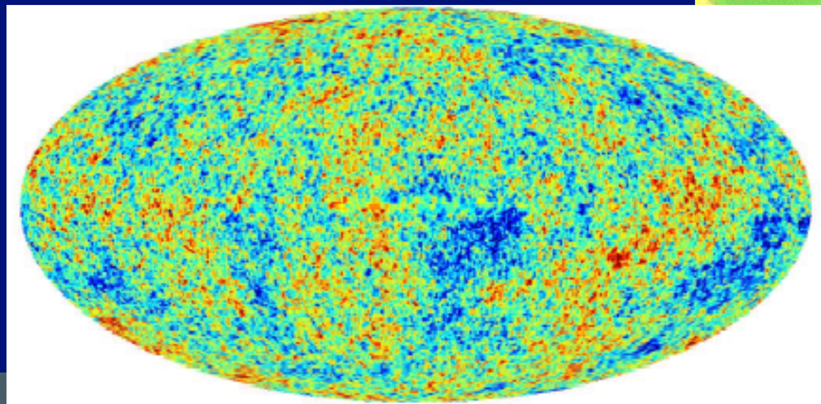
  lightest sparticle χ:

WMAP:

$$0.094 < \Omega_\chi h^2 < 0.124$$

g_μ - 2





Supersymmetric Models to Study

- Gravity-mediated:
  - NUHM2
    - as below, $m_{H_u} \neq m_{H_d}$
  - NUHM1
    - as below, c
  - CMSSM
    - m_0, $m_{1/2}$, ta
  - VCMSSM
    - as above, & A_0
  - mSUGRA
    - as above, & m_3
  - RPV CMSSM

Also studied in global fits

Most studied in global fits

Some Global fits

- Other SUSY × models:
  - Gauge-mediated
  - Anomaly-mediated
  - Mixed modulus-anomaly-mediated
  - parameter MSSM

Less studied in global fits

If model has N parameters, sample 100 values/parameter: 10^{2N} points, e.g., 10^8 in CMSSM

Data

- **Electroweak precision observables**
- **Flavour physics observables**
- g_μ - 2
- Higgs mass
- Dark matter
- **LHC**

MasterCode: O.Buchmueller, JE et al.

Observable	Source Th./Ex.	Constraint
m_t [GeV]	[39]	173.2 ± 0.90
$\Delta\alpha^{(5)}_{\rm had}(m_Z)$	[38]	0.02749 ± 0.00010
M_Z [GeV]	[40]	91.1875 ± 0.0021
Γ_Z [GeV]	[24] / [40]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[24] / [40]	41.540 ± 0.037
R_l	[24] / [40]	20.767 ± 0.025
$A_{\rm fb}(\ell)$	[24] / [40]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[24] / [40]	0.1465 ± 0.0032
R_b	[24] / [40]	0.21629 ± 0.00066
R_c	[24] / [40]	0.1721 ± 0.0030
$A_{\rm fb}(b)$	[24] / [40]	0.0992 ± 0.0016
$A_{\rm fb}(c)$	[24] / [40]	0.0707 ± 0.0035
A_b	[24] / [40]	0.923 ± 0.020
A_c	[24] / [40]	0.670 ± 0.027
A_ℓ(SLD)	[24] / [40]	0.1513 ± 0.0021
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[24] / [40]	0.2324 ± 0.0012
M_W [GeV]	[24] / [40]	$80.399 \pm 0.023 \pm 0.010_{\rm SUSY}$
$\mathrm{BR}^{\rm EXP}_{b\to s\gamma}/\mathrm{BR}^{\rm SM}_{b\to s\gamma}$	[41] / [42]	$1.117 \pm 0.076_{\rm EXP}$ $\pm 0.082_{\rm SM} \pm 0.050_{\rm SUSY}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	[27] / [37]	$(< 1.08 \pm 0.02_{\rm SUSY}) \times 10^{-8}$
$\mathrm{BR}^{\rm EXP}_{B\to\tau\nu}/\mathrm{BR}^{\rm SM}_{B\to\tau\nu}$	[27] / [42]	$1.43 \pm 0.43_{\rm EXP+TH}$
$\mathrm{BR}(B_d \to \mu^+\mu^-)$	[27] / [42]	$< (4.6 \pm 0.01_{\rm SUSY}) \times 10^{-9}$
$\mathrm{BR}^{\rm EXP}_{B\to X_s\ell\ell}/\mathrm{BR}^{\rm SM}_{B\to X_s\ell\ell}$	[43]/ [42]	0.99 ± 0.32
$\mathrm{BR}^{\rm EXP}_{K\to\mu\nu}/\mathrm{BR}^{\rm SM}_{K\to\mu\nu}$	[27] / [44]	$1.008 \pm 0.014_{\rm EXP+TH}$
$\mathrm{BR}^{\rm EXP}_{K\to\pi\nu\bar\nu}/\mathrm{BR}^{\rm SM}_{K\to\pi\nu\bar\nu}$	[45]/ [46]	< 4.5
$\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s}$	[45] / [47, 48]	$0.97 \pm 0.01_{\rm EXP} \pm 0.27_{\rm SM}$
$\frac{(\Delta M^{\rm EXP}_{B_s}/\Delta M^{\rm SM}_{B_s})}{(\Delta M^{\rm EXP}_{B_d}/\Delta M^{\rm SM}_{B_d})}$	[27] / [42, 47, 48]	$1.00 \pm 0.01_{\rm EXP} \pm 0.13_{\rm SM}$
$\Delta\epsilon^{\rm EXP}_K/\Delta\epsilon^{\rm SM}_K$	[45] / [47, 48]	$1.08 \pm 0.14_{\rm EXP+TH}$
$a^{\rm EXP}_\mu - a^{\rm SM}_\mu$	[49] / [38, 50]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
M_h [GeV]	[26] / [51, 52]	$> 114.4 \pm 1.5_{\rm SUSY}$
$\Omega_{\rm CDM}h^2$	[29] / [53]	$0.1109 \pm 0.0056 \pm 0.012_{\rm SUSY}$
$\sigma^{\rm SI}_p$	[23]	$(m_{\tilde\chi^0_1}, \sigma^{\rm SI}_p)$ plane
jets + $\not\!\!E_T$	[16, 18]	$(m_0, m_{1/2})$ plane
$H/A, H^\pm$	[19]	$(M_A, \tan\beta)$ plane

Dark Matter Observables

- Cosmological cold dark matter density
  - $\Omega_{CDM}\, h^2 = 0.1109 \pm 0.0056$
- Reduces dimensionality of SUSY space by ~ 1
  - Could be other sources of DM: little effect
- Upper limit on spin-independent scattering
- Other astrophysical constraints?
  - Annihilations inside Sun/Earth → neutrinos?
  - Anomalies in cosmic-ray γ/e+/e- spectra?
- Not explicable in models discussed here

Impact of LHC on the CMSSM

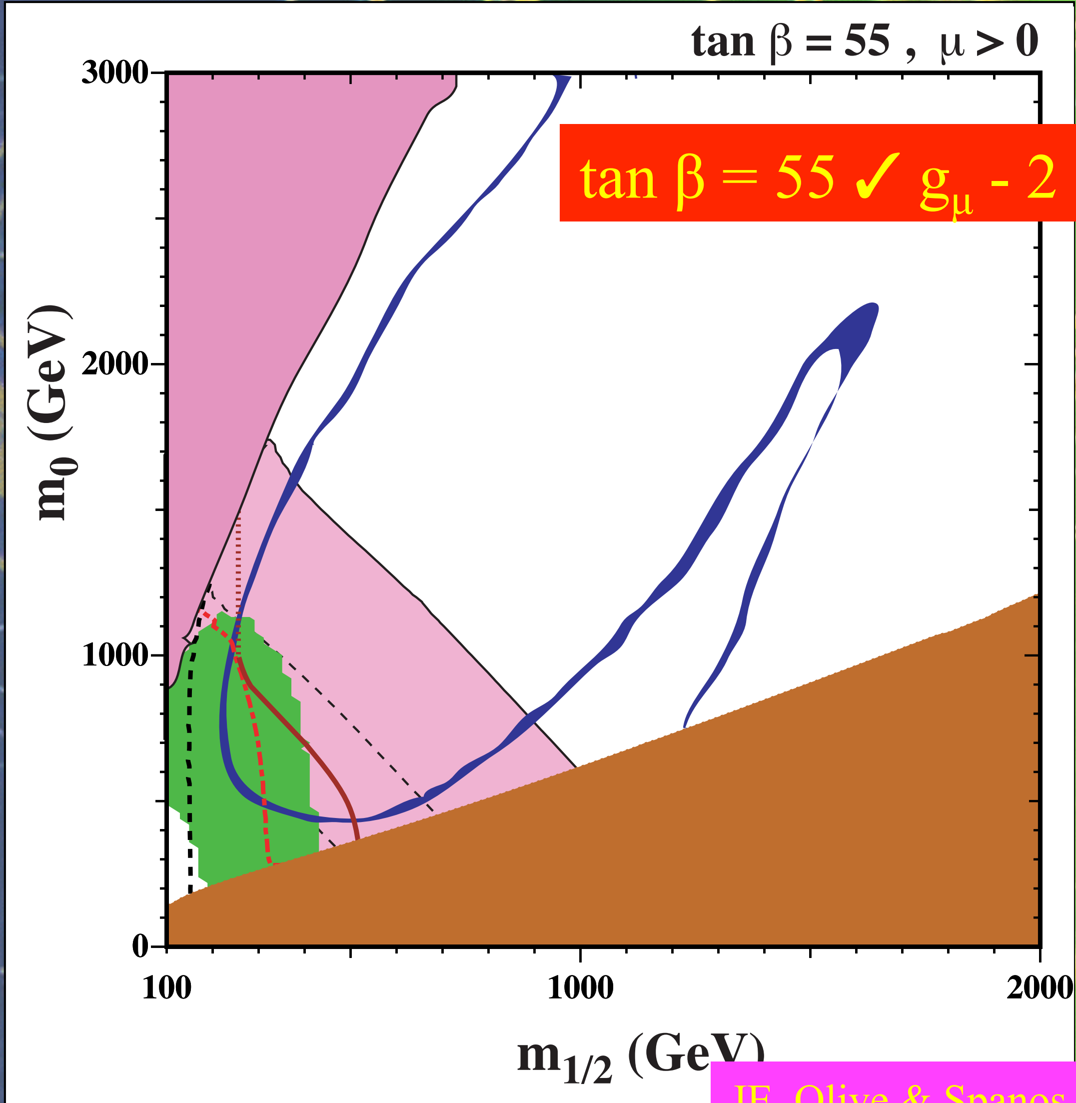
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

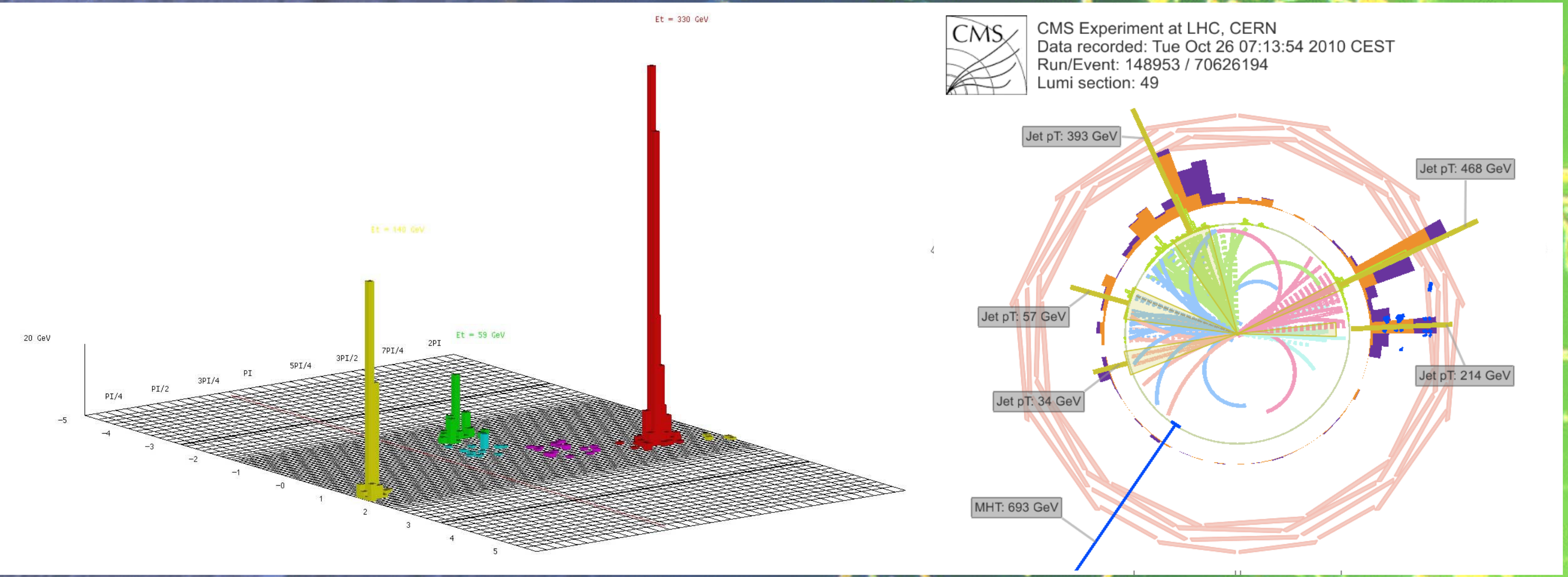
WMAP constraint on CDM density

Preferred (?) by latest g - 2



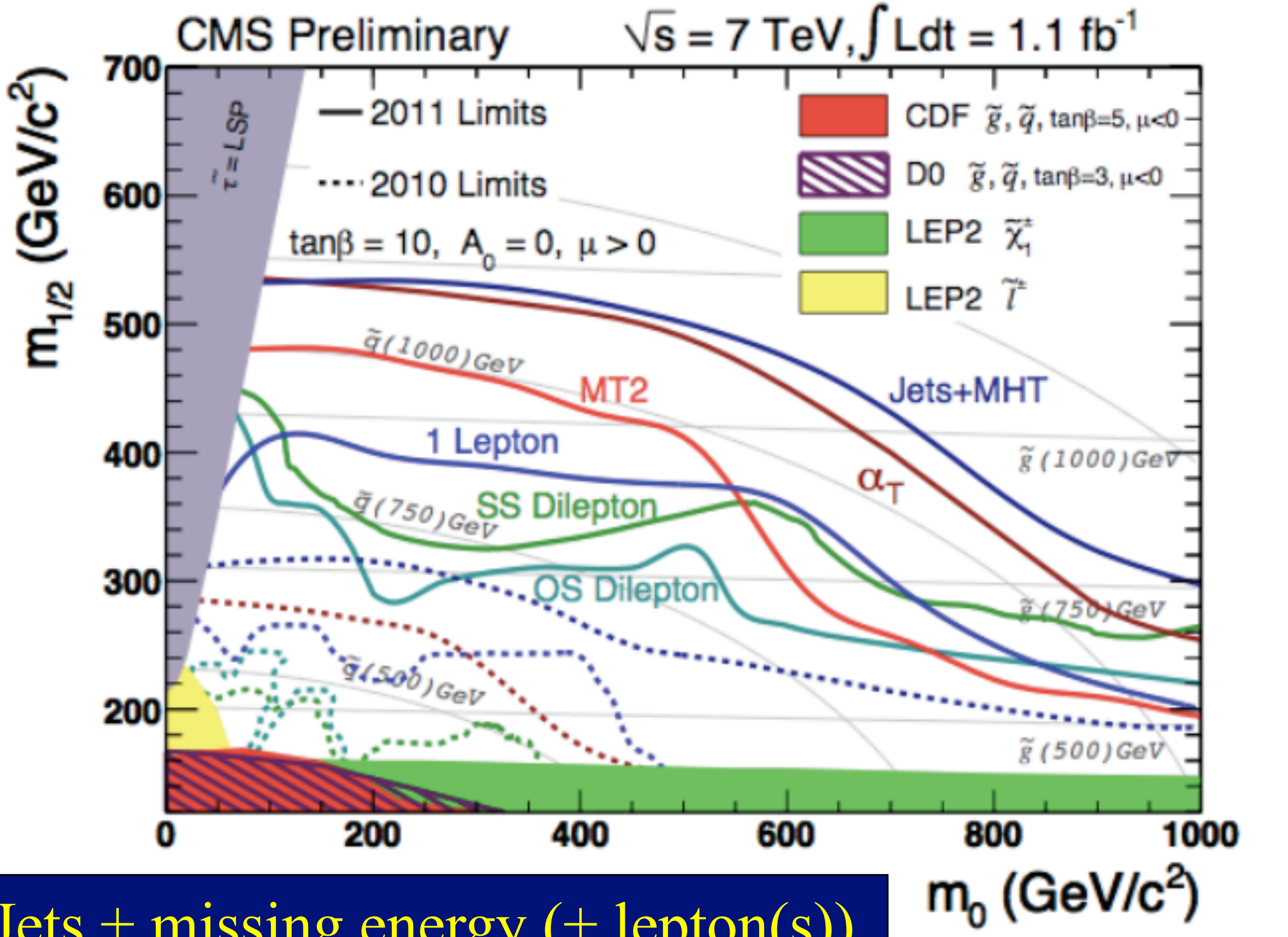
JE, Olive & Spanos

Supersymmetric Signature @ LHC



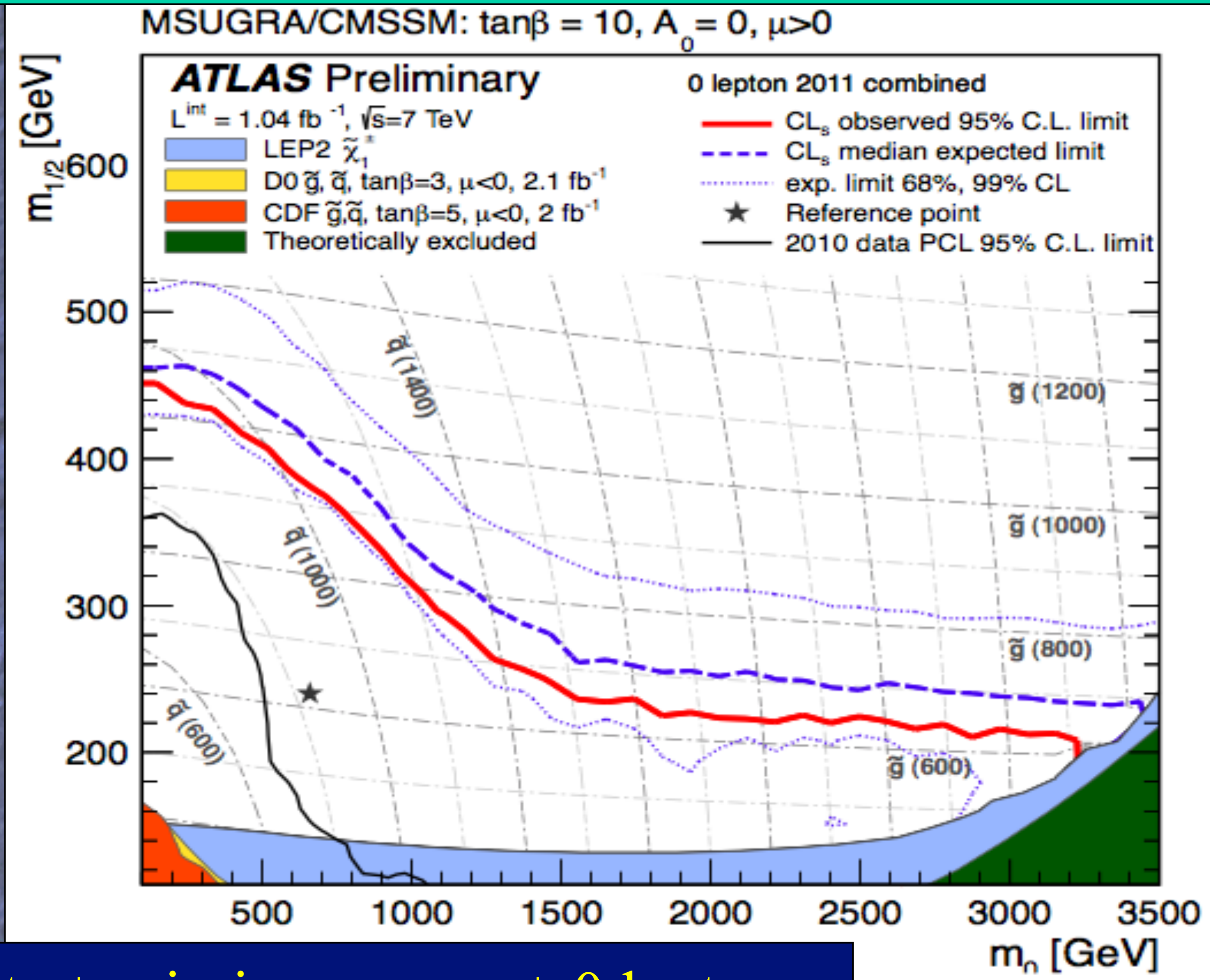
Missing transverse energy carried away by dark matter particles

Supersymmetry Searches in CMS



Jets + missing energy (+ lepton(s))

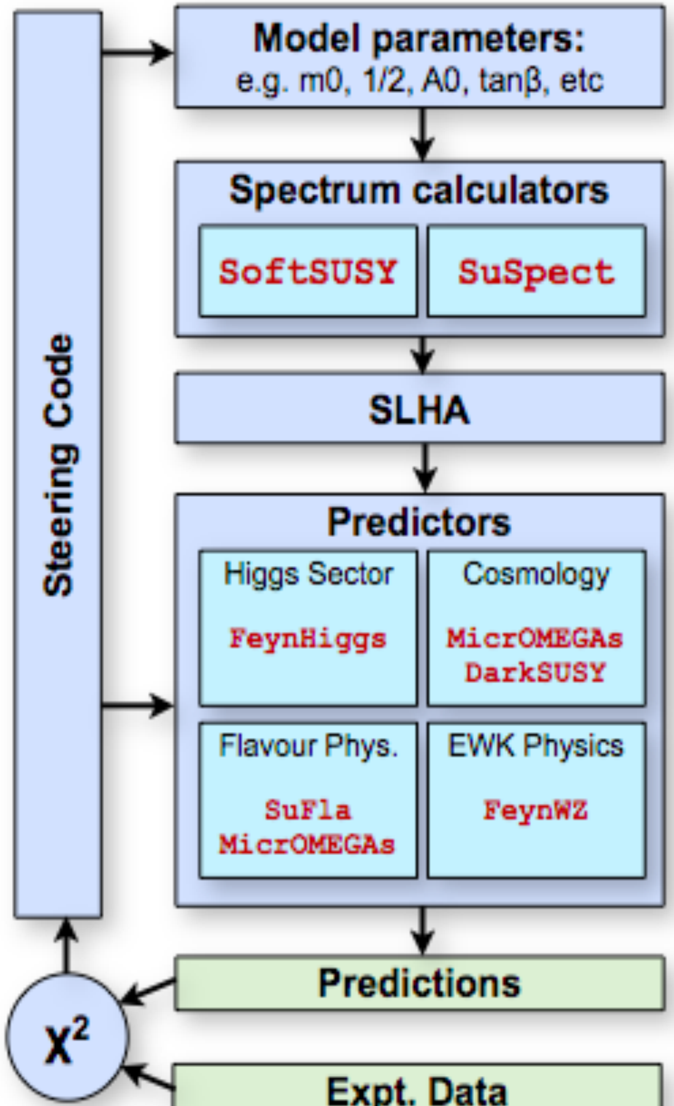
Supersymmetry Searches in ATLAS



Jets + missing energy + 0 lepton

MasterCode

- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- **Compatibility is crucial! Ensured by**
  - close collaboration of tools authors
  - standard interfaces

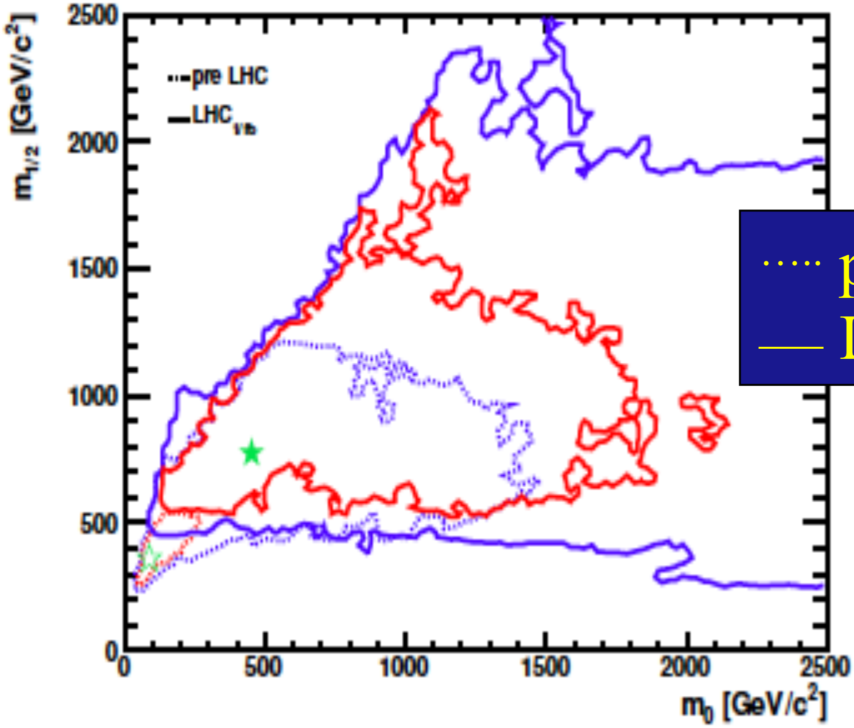


O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

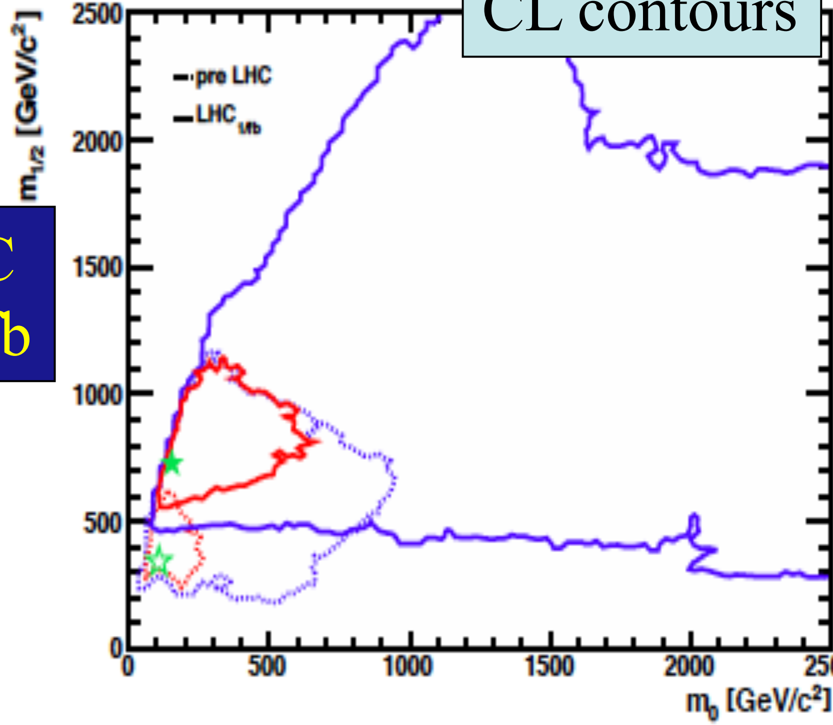
Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

68% & 95% CL contours



..... pre-LHC
— LHC 1/fb



CMSSM
60 million points sampled

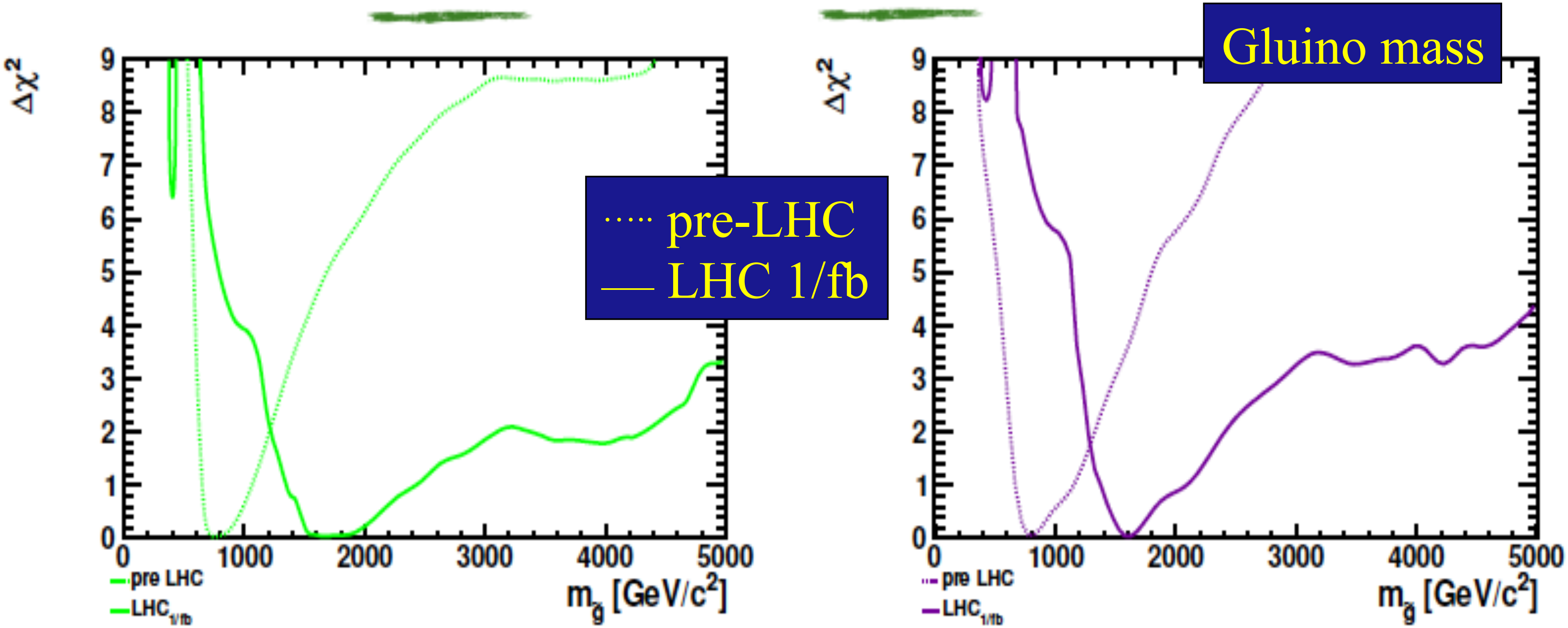
NUHM1
70 million points sampled

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

Preferred region "opens up" at cost of worsening global χ^2 value!

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



CMSSM

60 million points sampled

NUHM1

70 million points sampled

Favoured values of gluino mass significantly above pre-LHC, > 1 TeV

Strategies for Detecting Supersymmetric Dark Matter

- Scattering on nucleus in laboratory

  $\chi + A \rightarrow \chi + A$

- Annihilation in core of Sun or Earth

  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

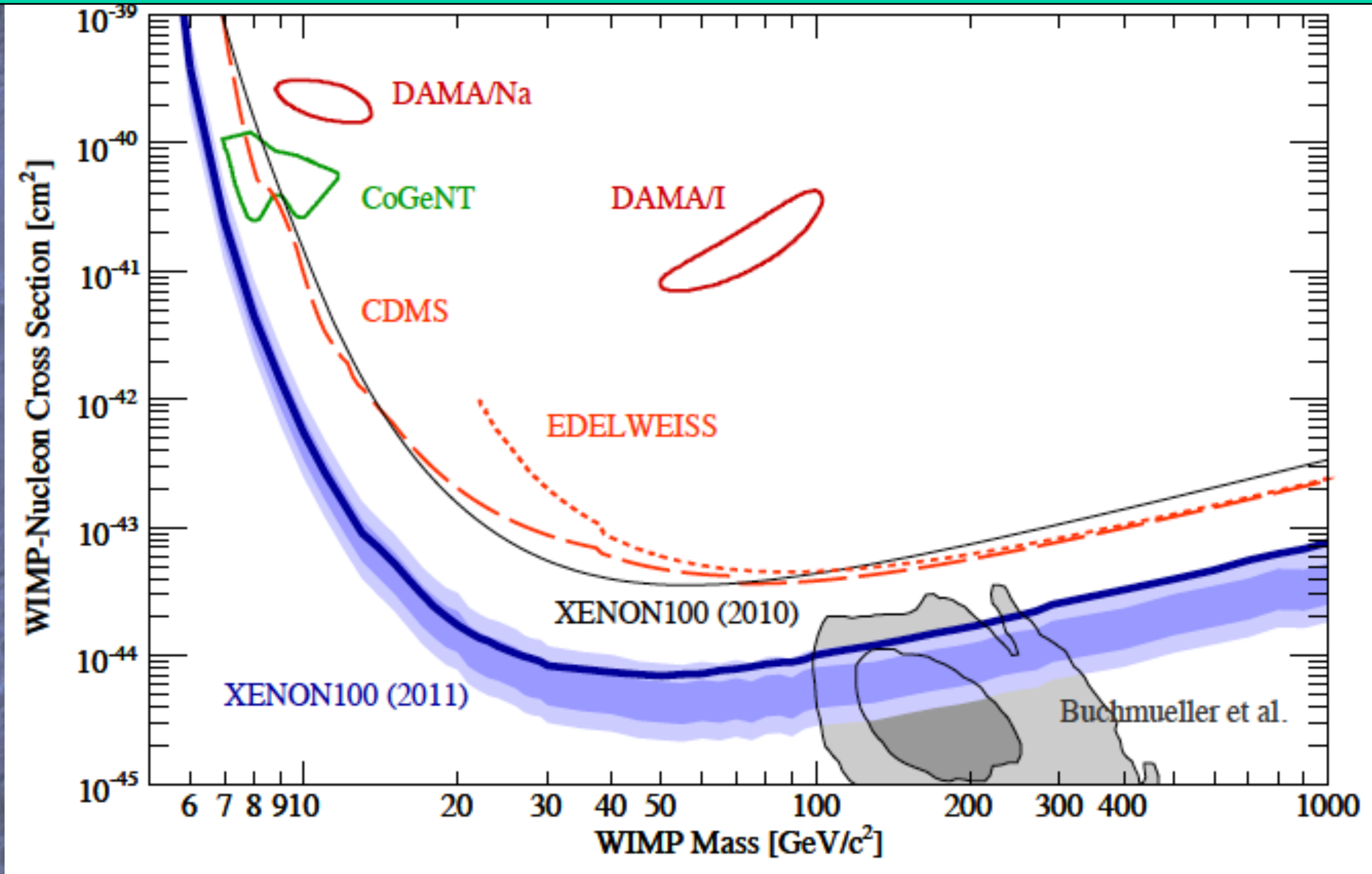
- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots ?$

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?

XENON100 Experiment



Aprile et al: arXiv:1104.2549

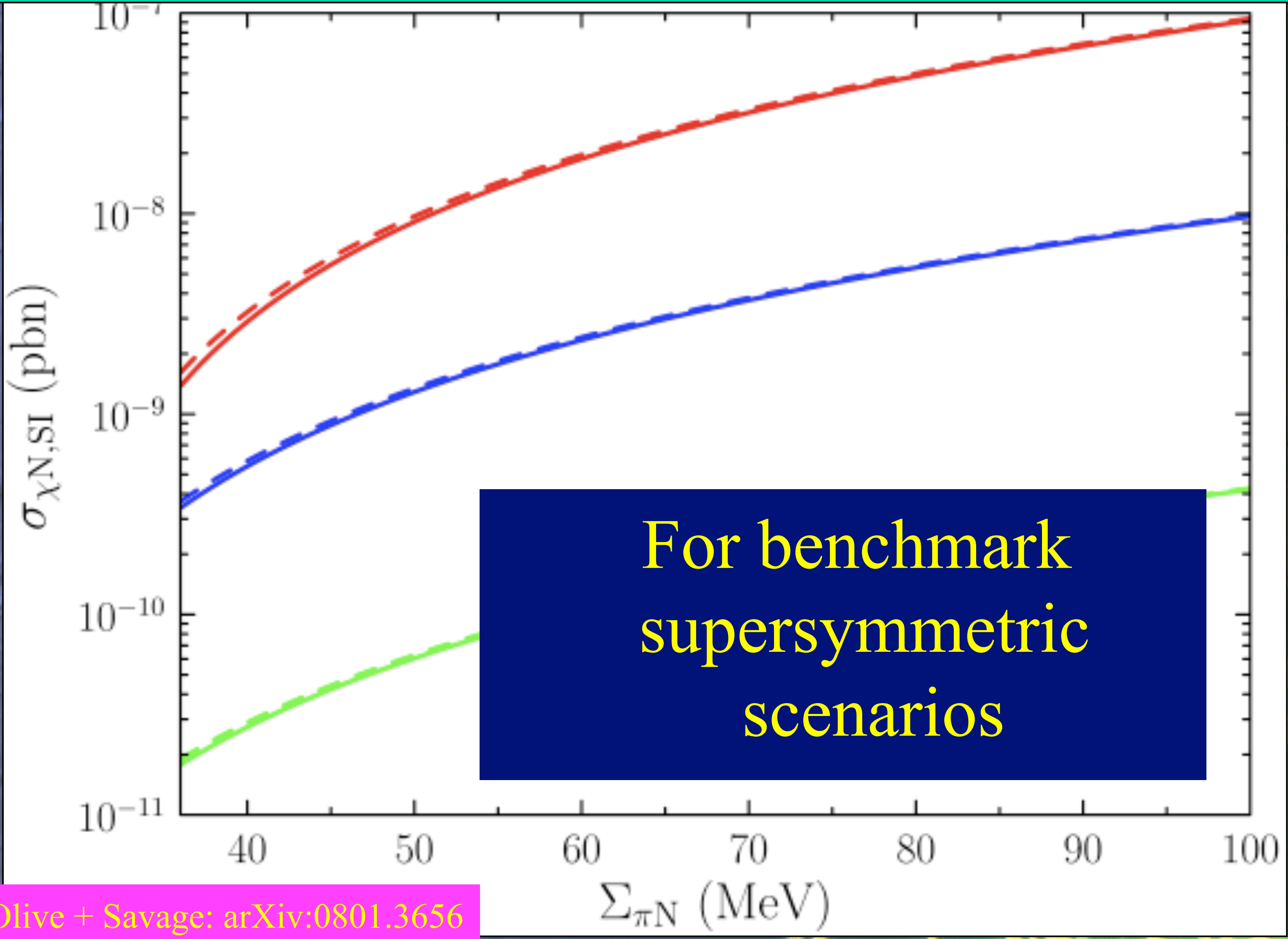
Importance of the π-N σ Term ($\Sigma_{\pi N}$)

- Higgs exchange important for spin-independent DM scattering
- **Sensitive to $\langle N|\bar{s}s|N\rangle$**
- Baryon masses: $\sigma_0 = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$

  $= 36 \pm 7$ MeV
- Cf, $\Sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d|N\rangle$
- Strangeness ratio $y = \langle N|2\bar{s}s|N\rangle / \langle N|\bar{u}u + \bar{d}d|N\rangle$

  $= 1 - \sigma_0/\Sigma_{\pi N}$
- Some experiments suggest large value of $\Sigma_{\pi N} = 64 \pm 8$ MeV, hence y large
- Some lattice calculations suggest y small

Sensitivity to π-N Scattering σ Term



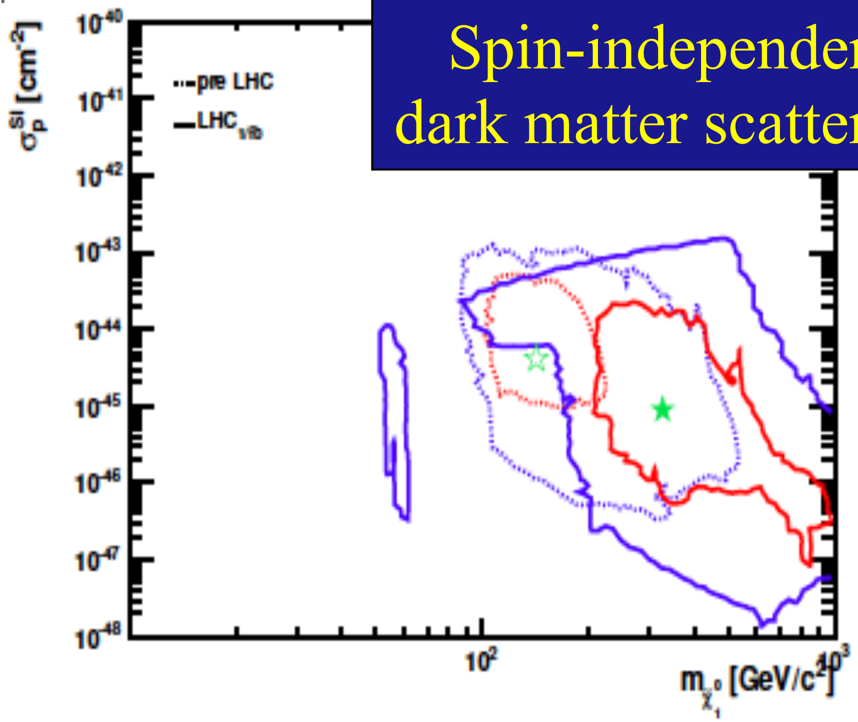
JE + Olive + Savage: arXiv:0801.3656

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

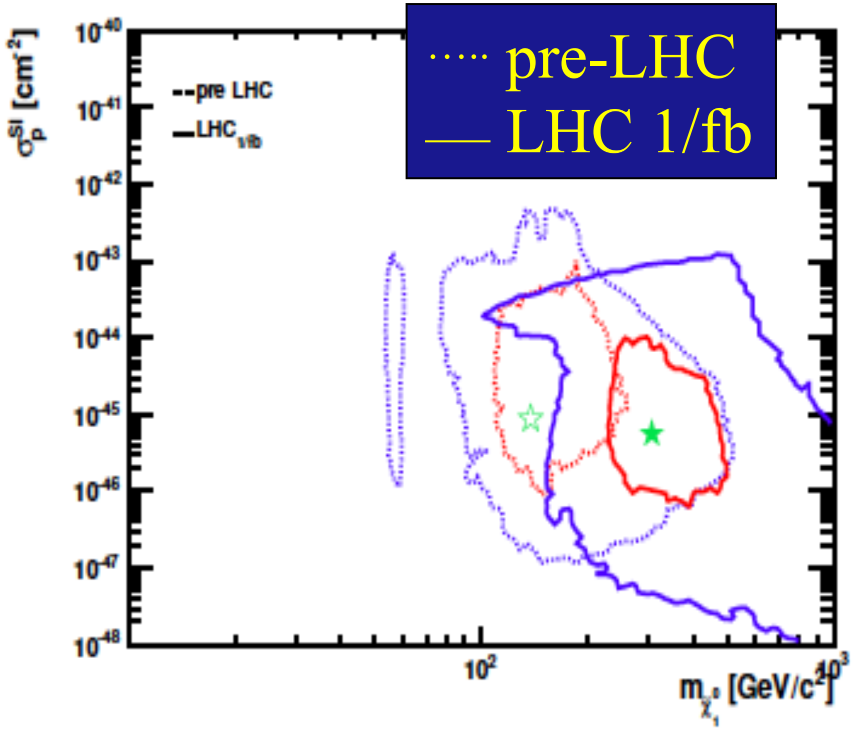
Spin-independent dark matter scattering

····· pre-LHC
— LHC 1/fb



CMSSM

60 million points sampled



NUHM1

70 million points sampled

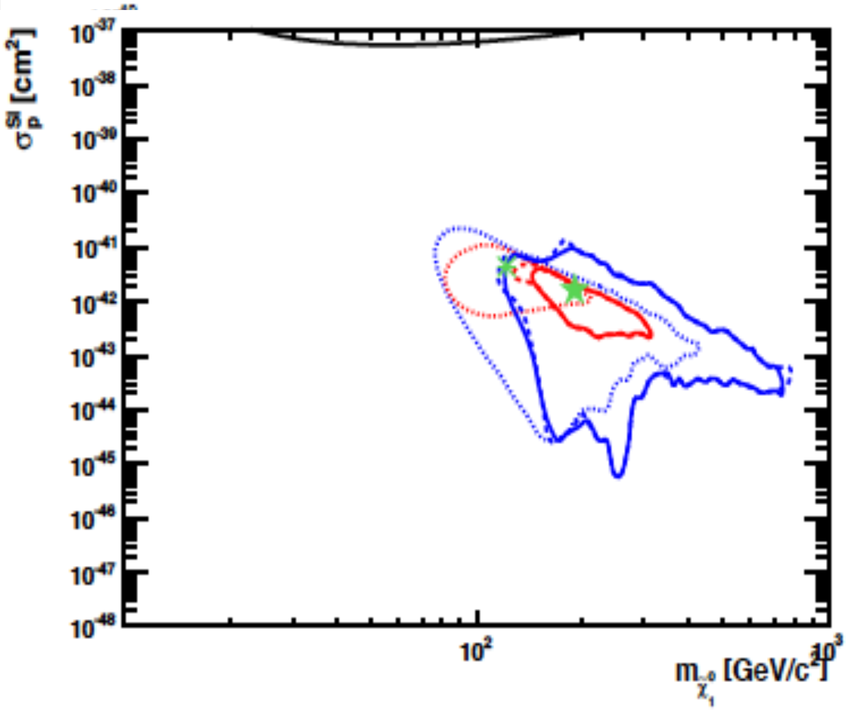
Significant impact of XENON100 experiment:
Prospects for coming years !

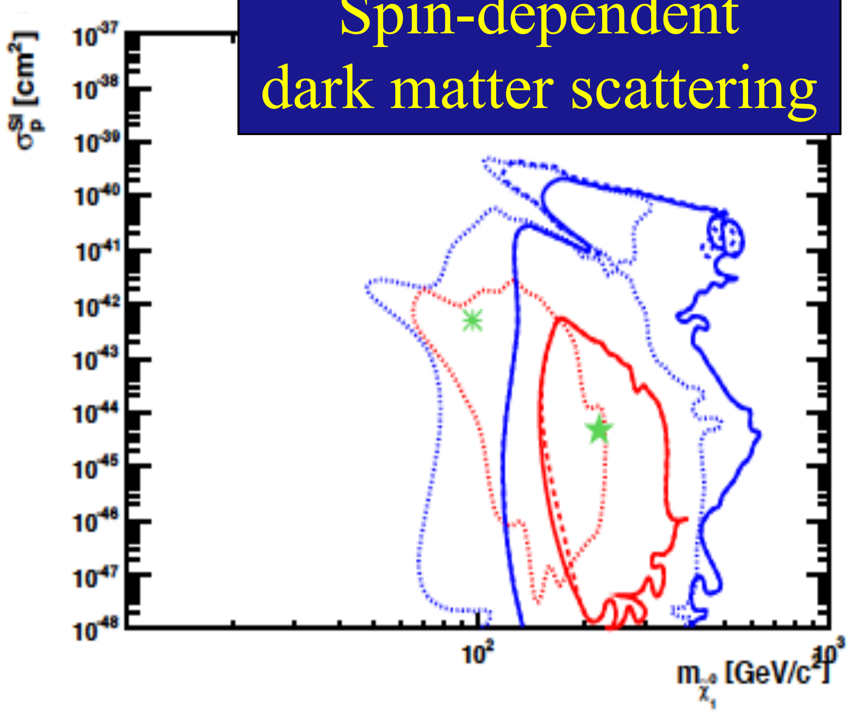
Post-LHC, Post-XENON100

mastercode

2010 **ATLAS + CMS with** 35pb^{-1} **LHC Data**

Spin-dependent dark matter scattering





CMSSM

60 million points sampled

NUHM1

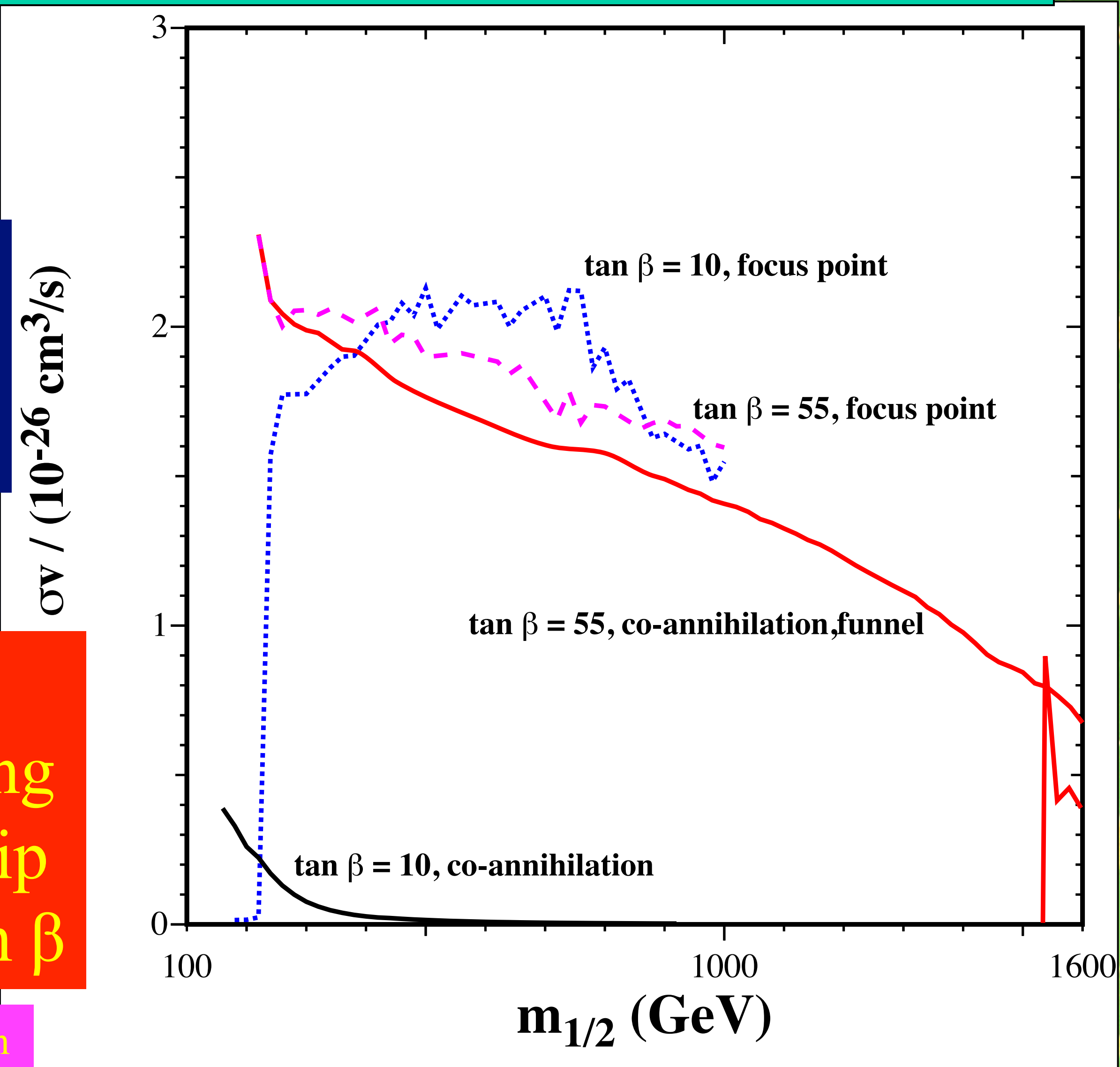
70 million points sampled

Much further below prospective experimental sensitivity ?

Neutralino Annihilation Rates

Small in coannihilation strip @ small tan β

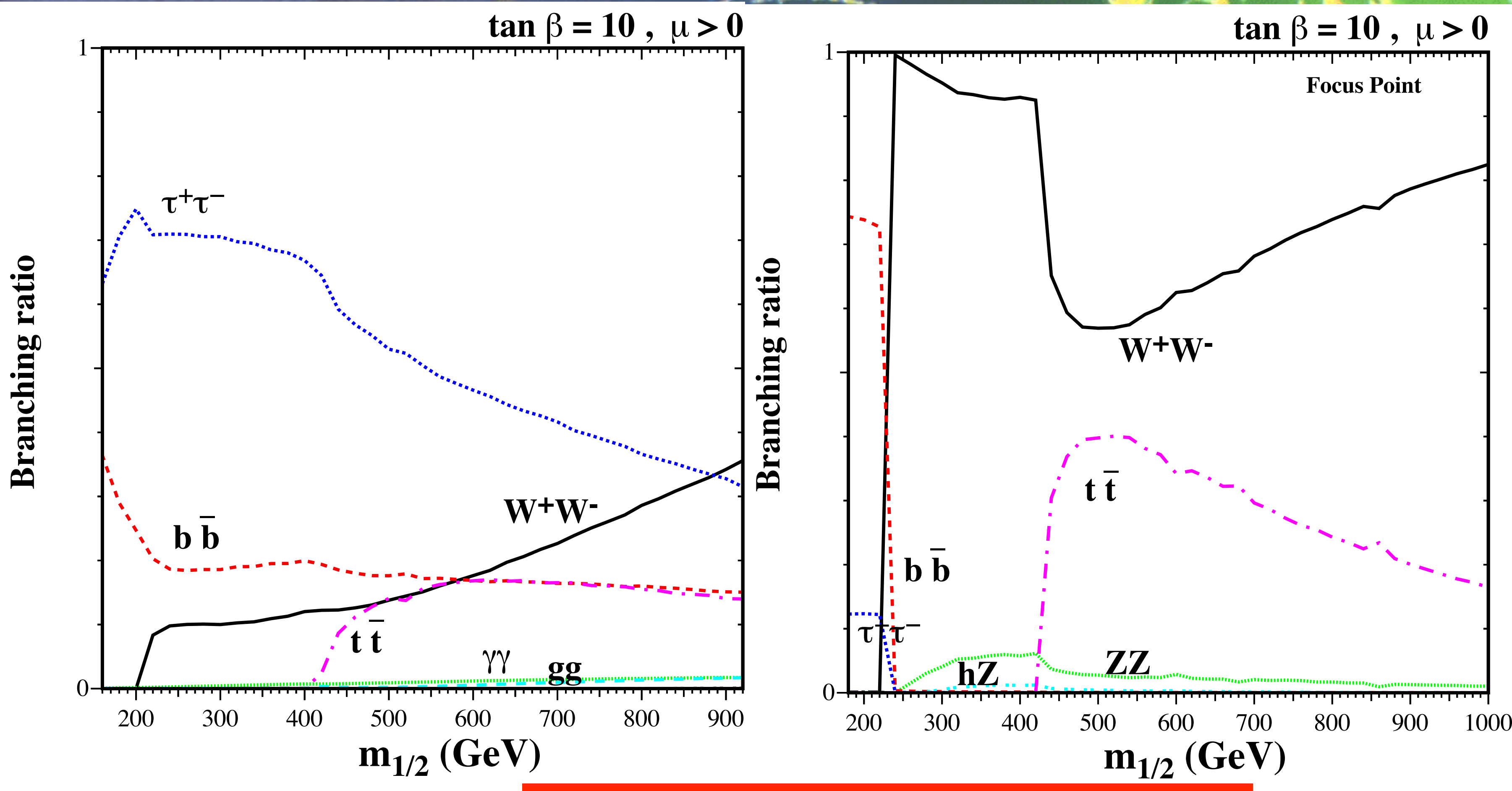
Constraints potentially along focus-point strip and @ large tan β



JE, Olive & Spanos: in preparation

Annihilation Branching Fractions

Vary in different regions of parameter space

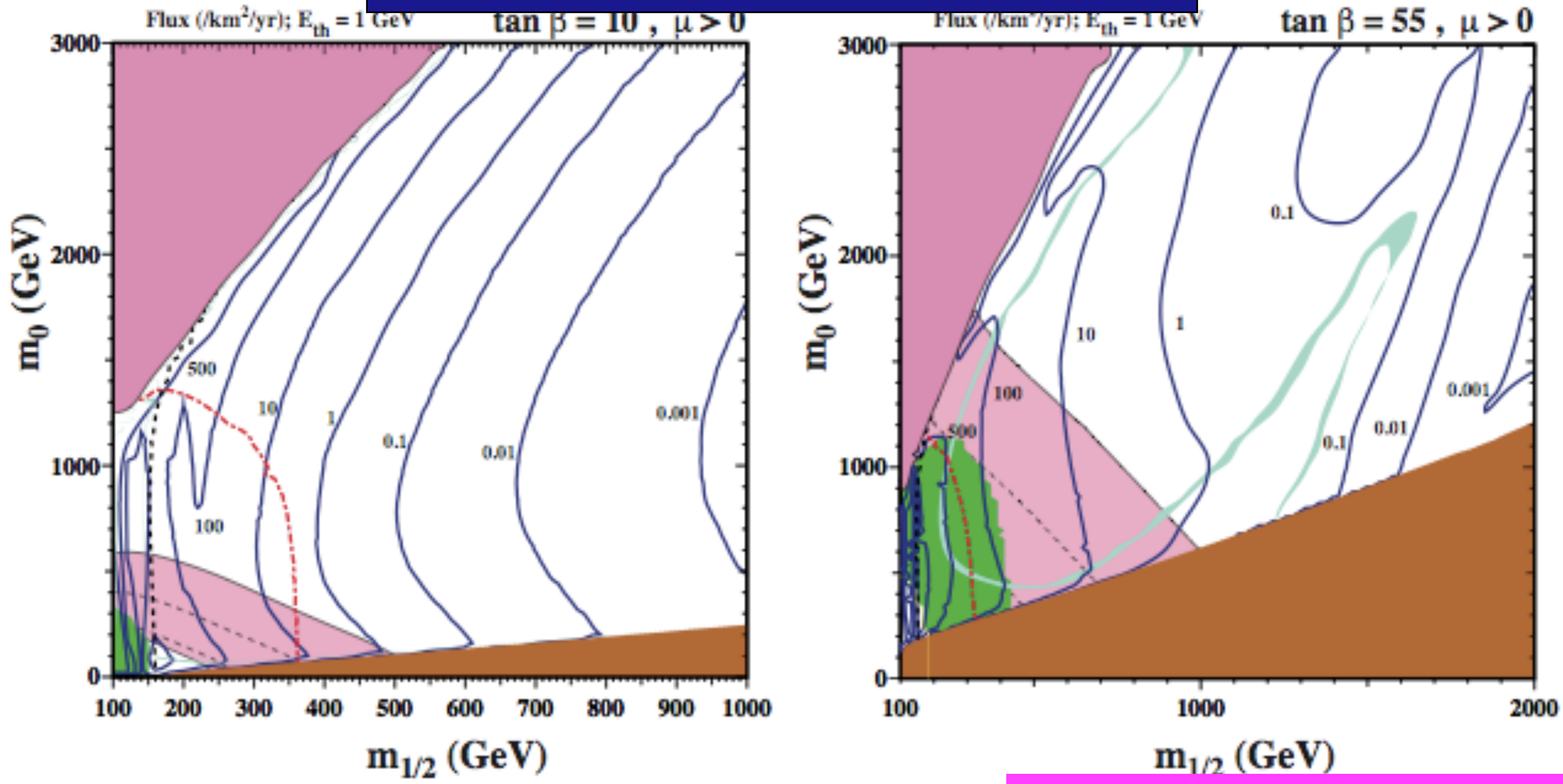


JE, Olive & Spanos: in preparation

Must be modelled correctly

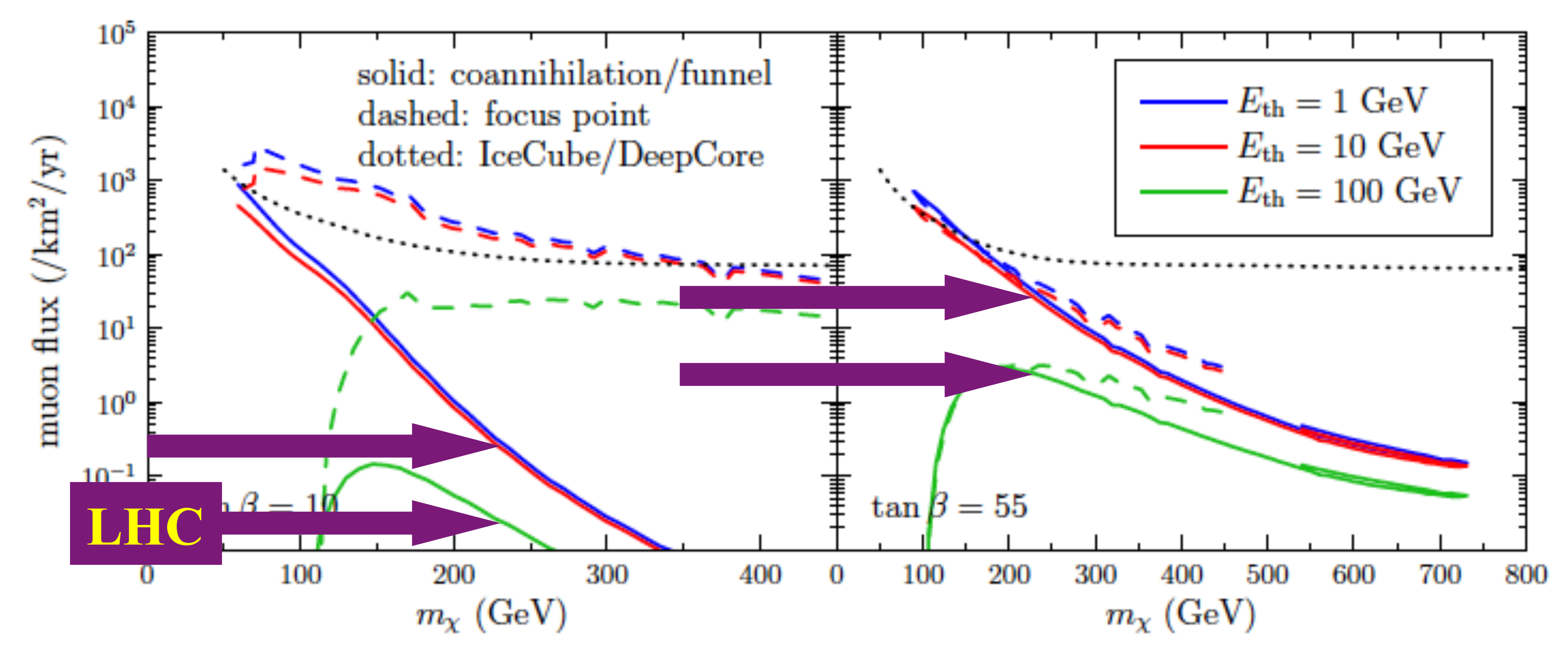
Neutrino Fluxes from CMSSM Dark Matter Annihilation in Sun

Neutrino flux above 1 GeV



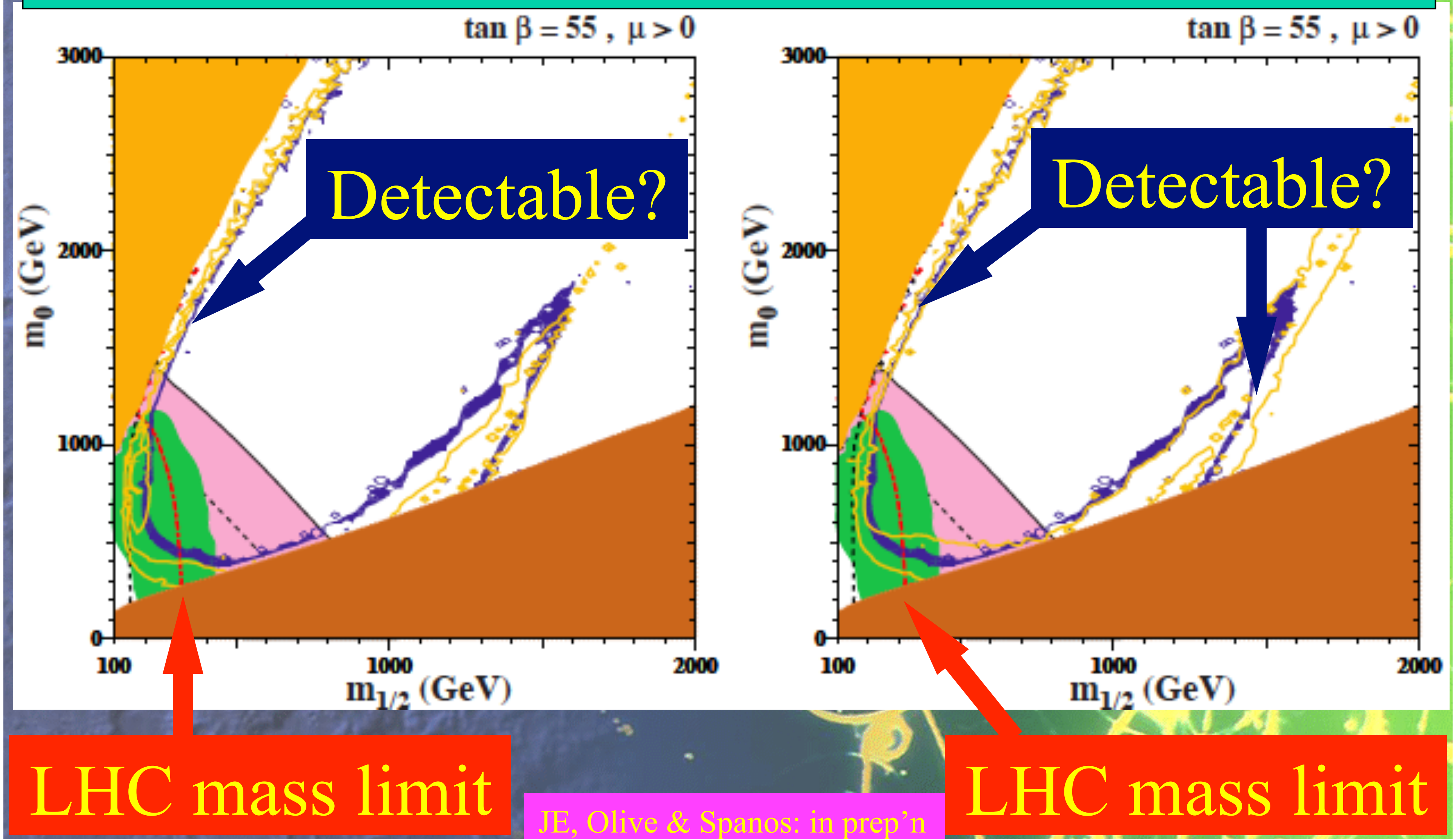
JE, Olive & Savage: arXiv:0912.3137

Neutrinos from Annihilations inside the Sun



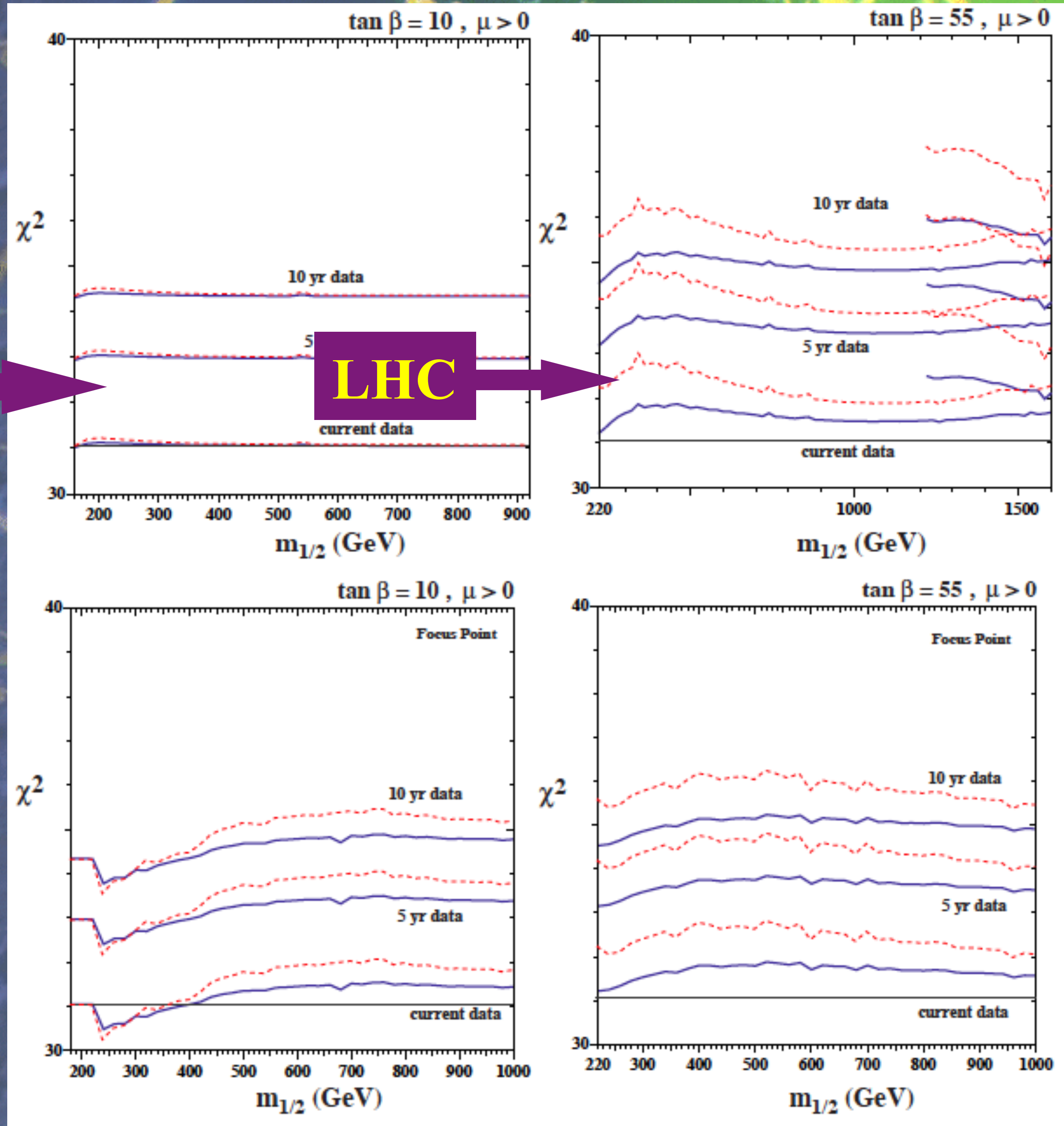
JE, Olive, Savage and Spanos: arXiv:0912.3137

Gamma Fluxes from Dark Matter Annihilation in the Galactic Centre



JE, Olive & Spanos: in prep'n

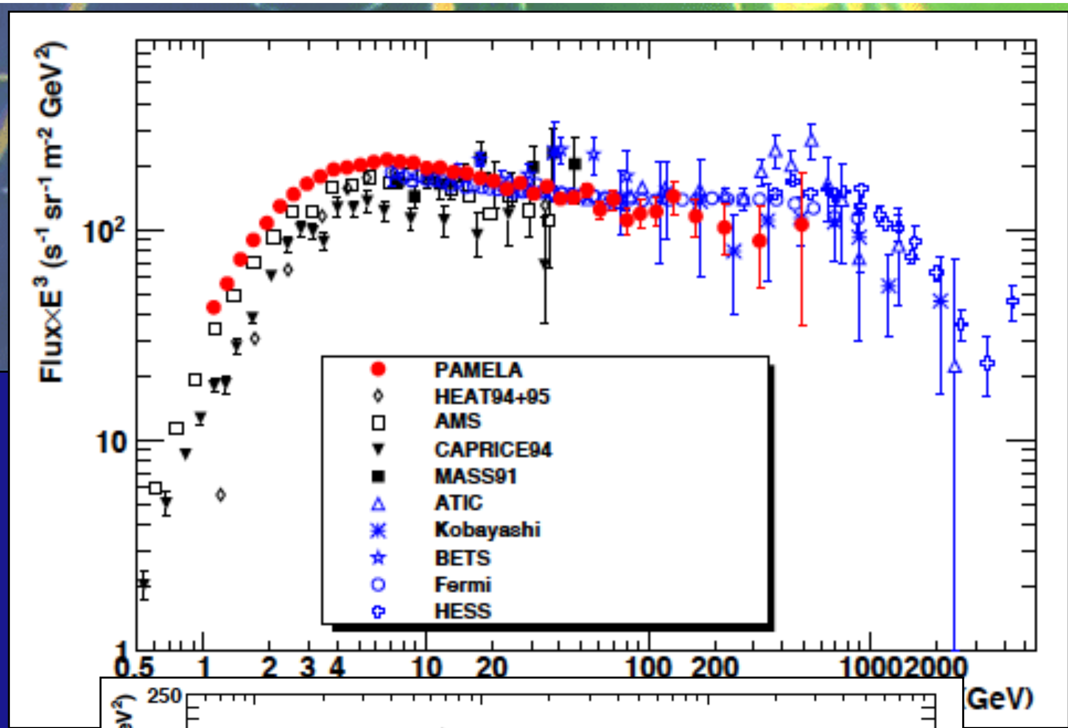
Gammas from Annihilations in the Centre of the Galaxy

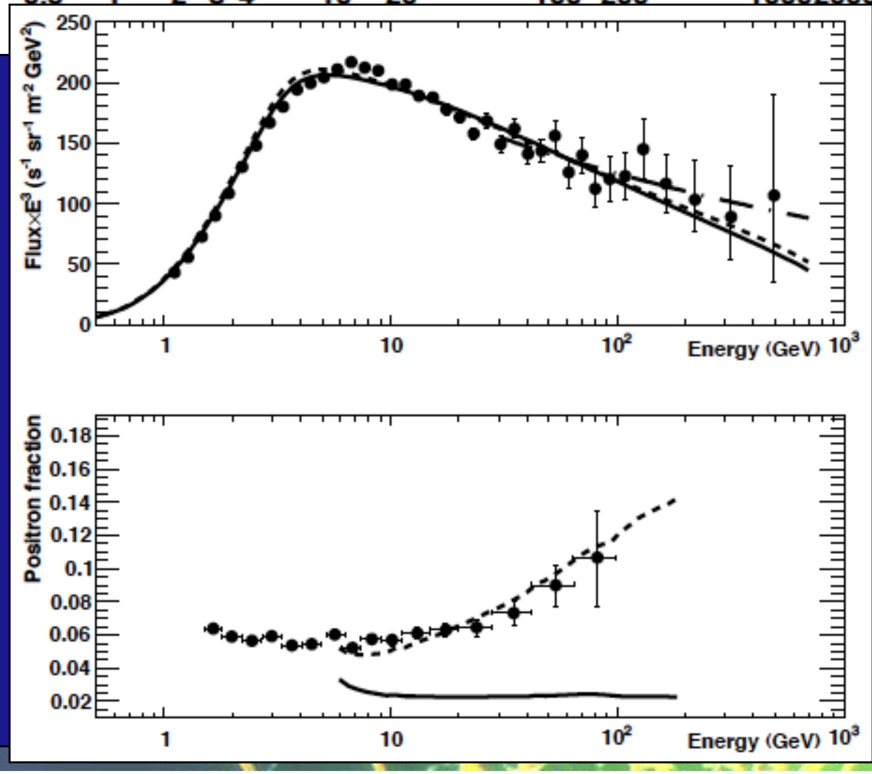


JE, Olive and Spanos: arXiv:1106.0768

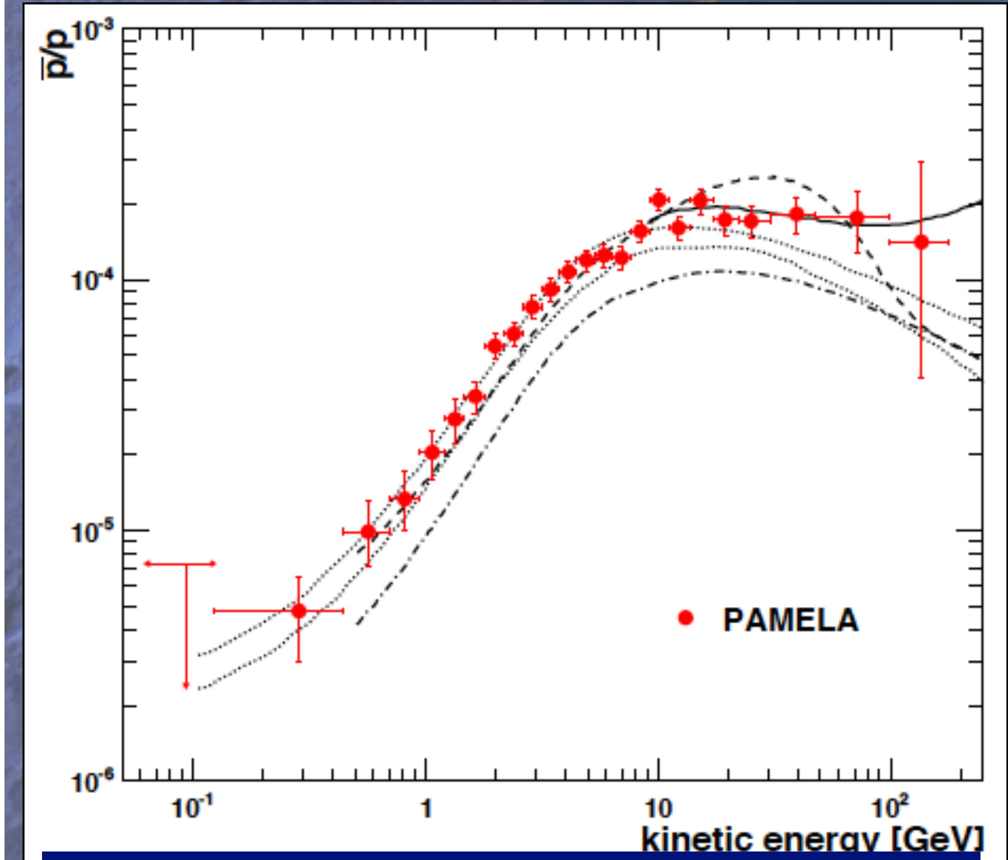
Anomalies in e^+/e^- Spectra?

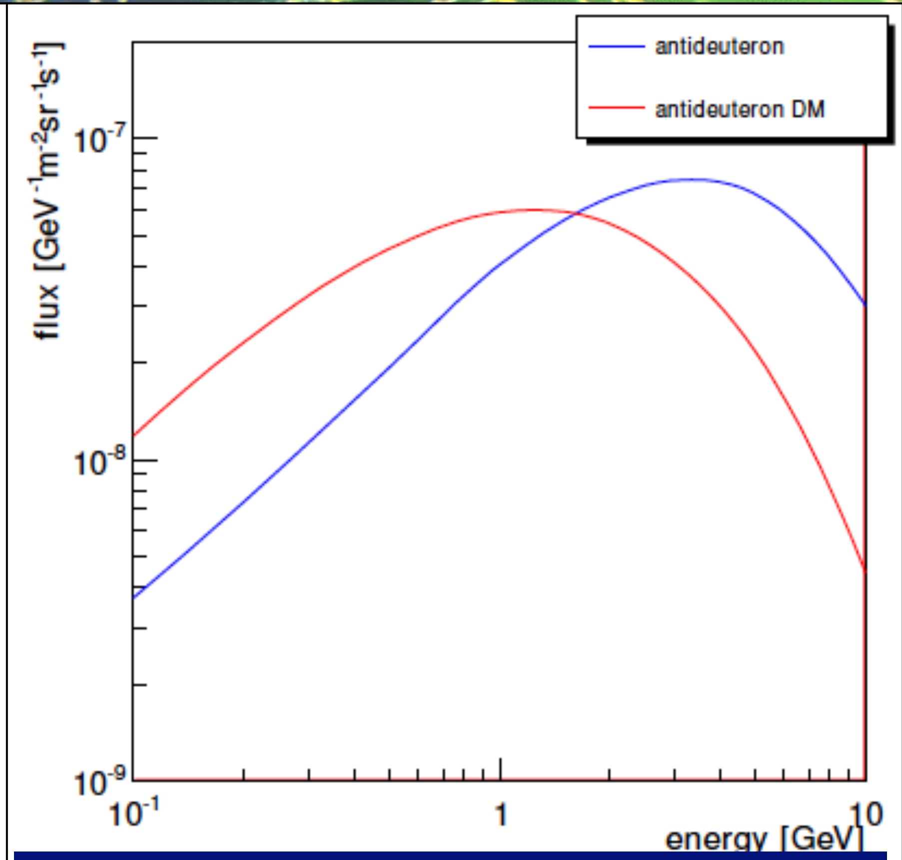
- Shoulder in $e^+ + e^-$ spectrum?
- Rising e^+/e^- ratio
- Uncertainties in cosmic-ray production, propagation?
- Nearby sources?
- SUSY interpretation difficult, unnecessary?





Antiprotons and Antideuterons from Dark Matter Annihilation?

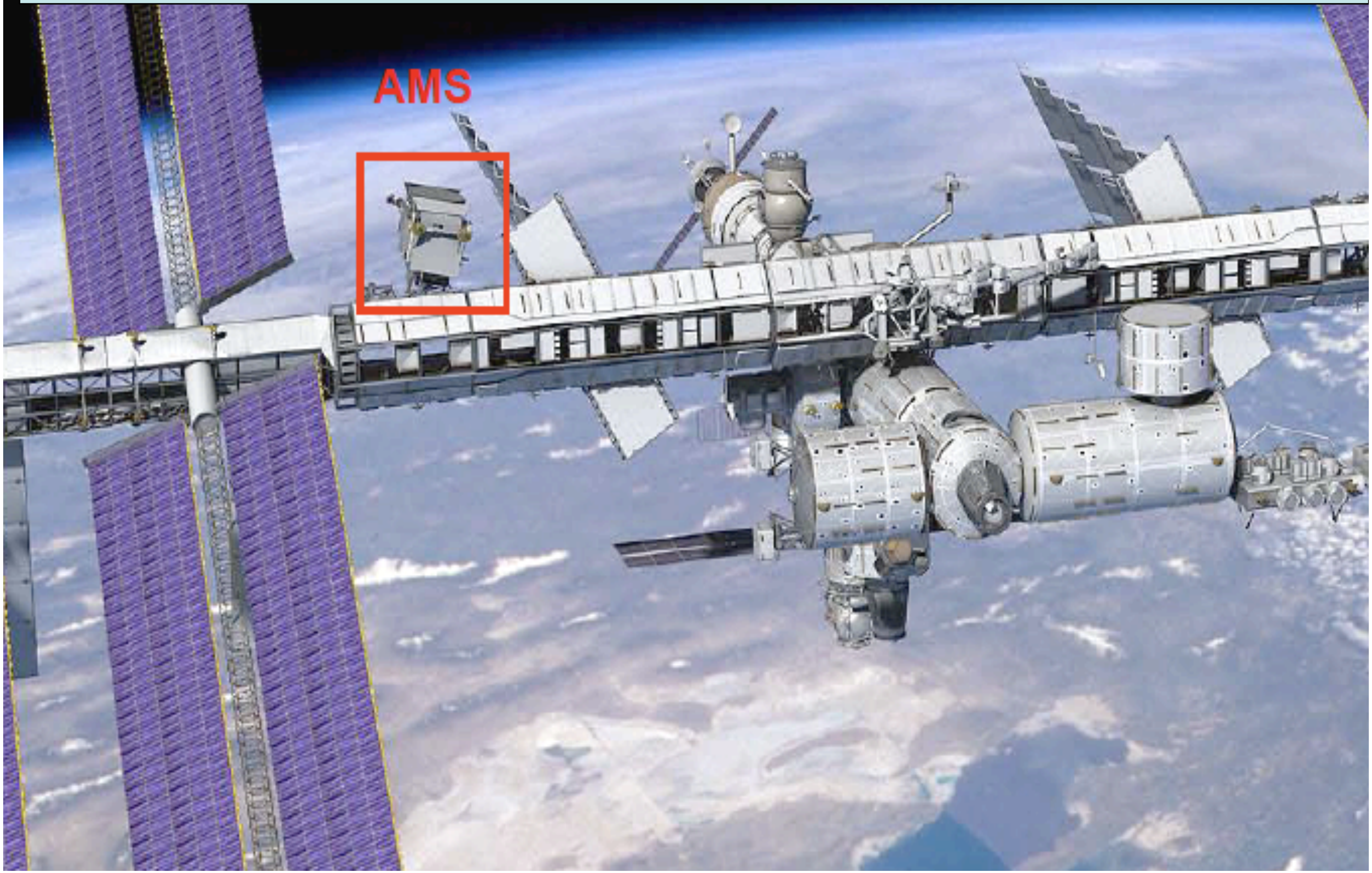




··· standard cosmic rays
--- possible supersymmetric model
— including production at source

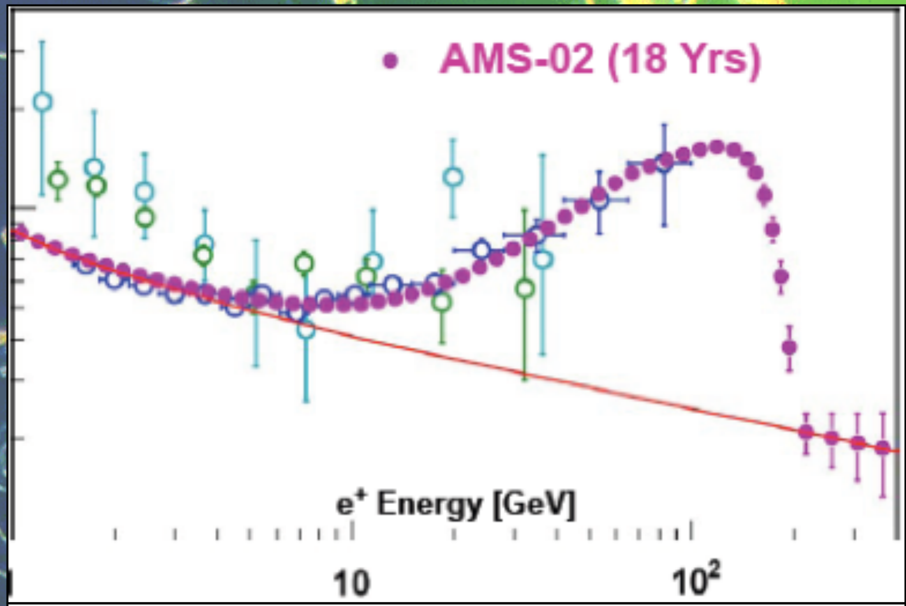
Antideuterons could provide another window of opportunity?

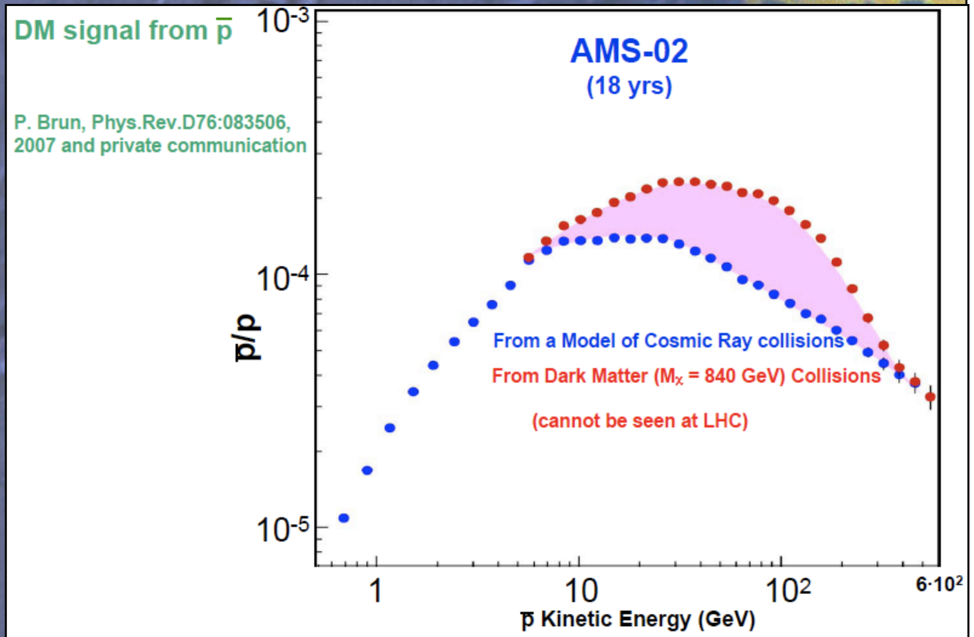
AMS-02 on the International Space Station (ISS)

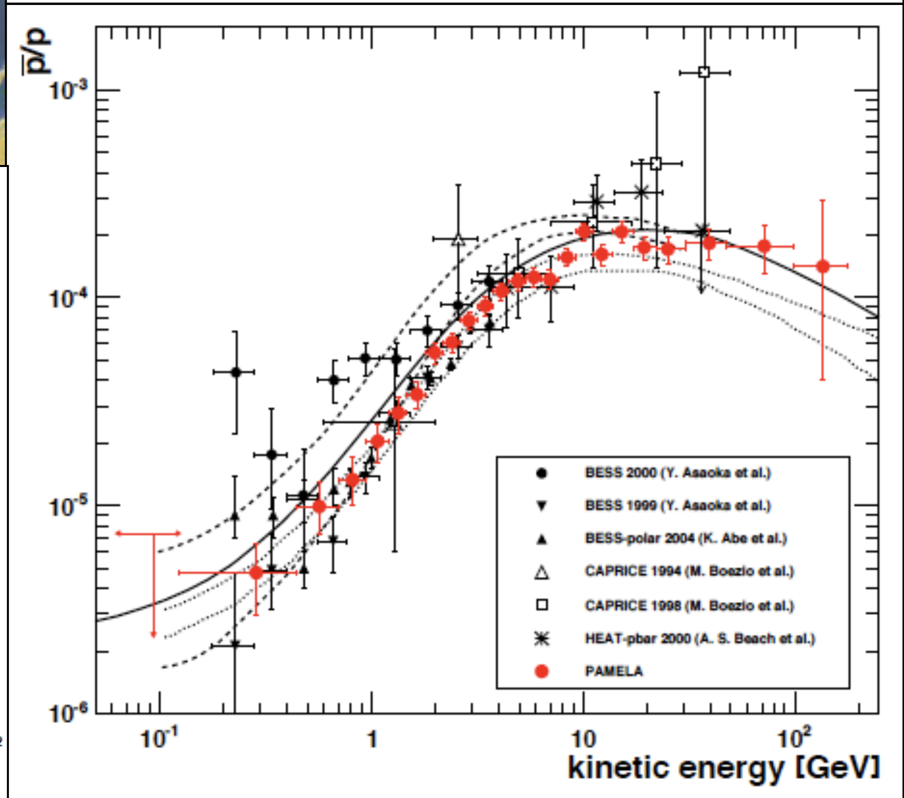


AMS-02 and Dark Matter

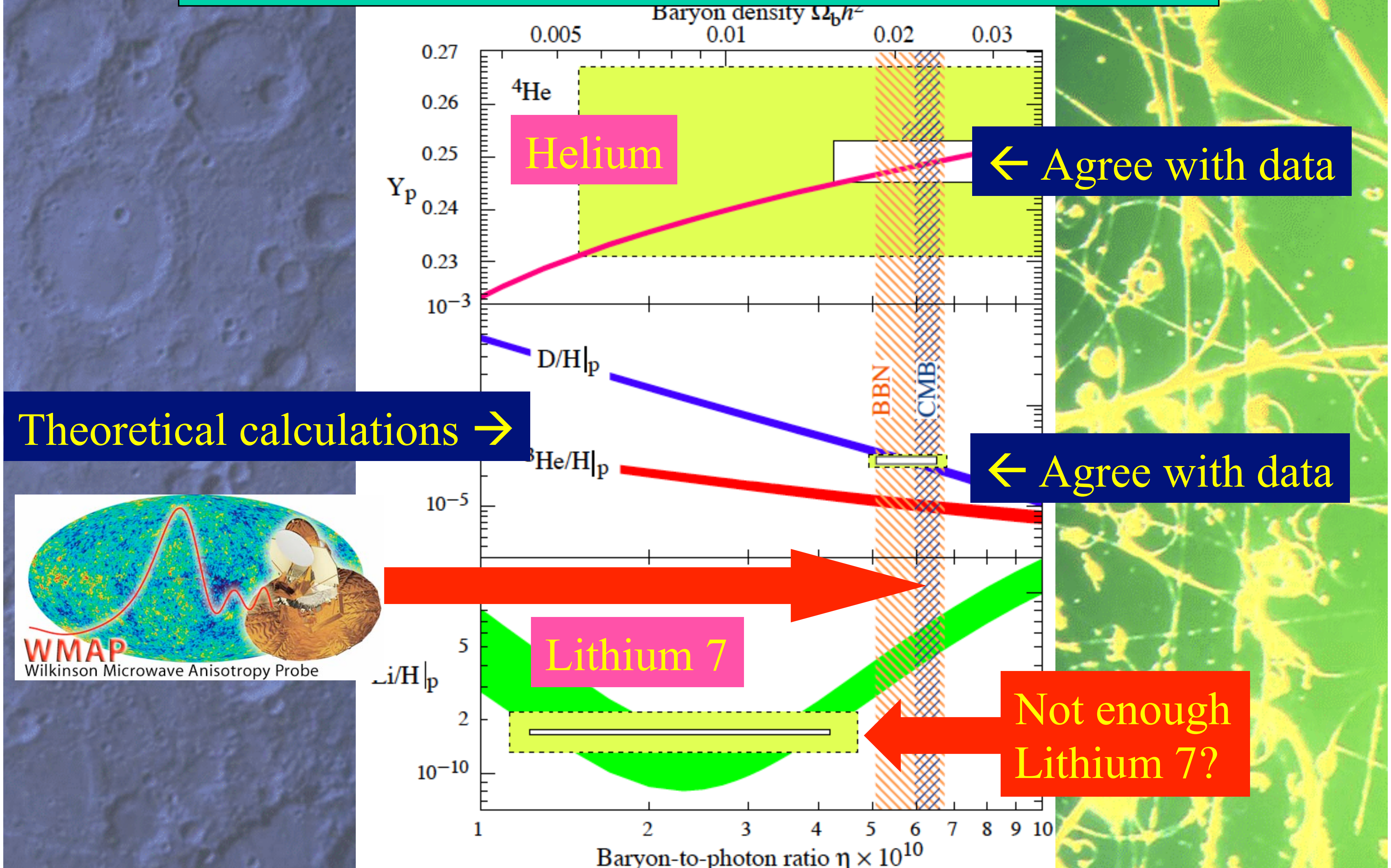
- Measurement of e^+ spectrum to higher E
- Precision measurement of antiproton spectrum







Cosmological Lithium Problem(s)



Also evidence for over-production of Lithium 6

Long-Lived Gravitino & BBN

- Conventional Big-Bang Nucleosynthesis calculations agree well with D, 3He, 4He data
- Constraints on abundance of long-lived relic
  - Apparent discrepancy for Lithium:

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{halo}\star} = (1.23^{+0.34}_{-0.16}) \times 10^{-10}$$

  - Globular clusters: $(2.34 \pm 0.05) \times 10^{-10}$
  - BBN calculation: $(5.12^{+0.71}_{-0.62}) \times 10^{-10}$
- **Can discrepancy be removed by decays of long-lived relic, e.g., gravitino?**

Cyburt, JE, Fields, Luo, Olive & Spanos: arXiv:1007.4173

Nuclear Reactions

- Relevant interactions of non-thermal particles from relic decay showers
- Incorporate errors in measurements
- Make global likelihood analysis

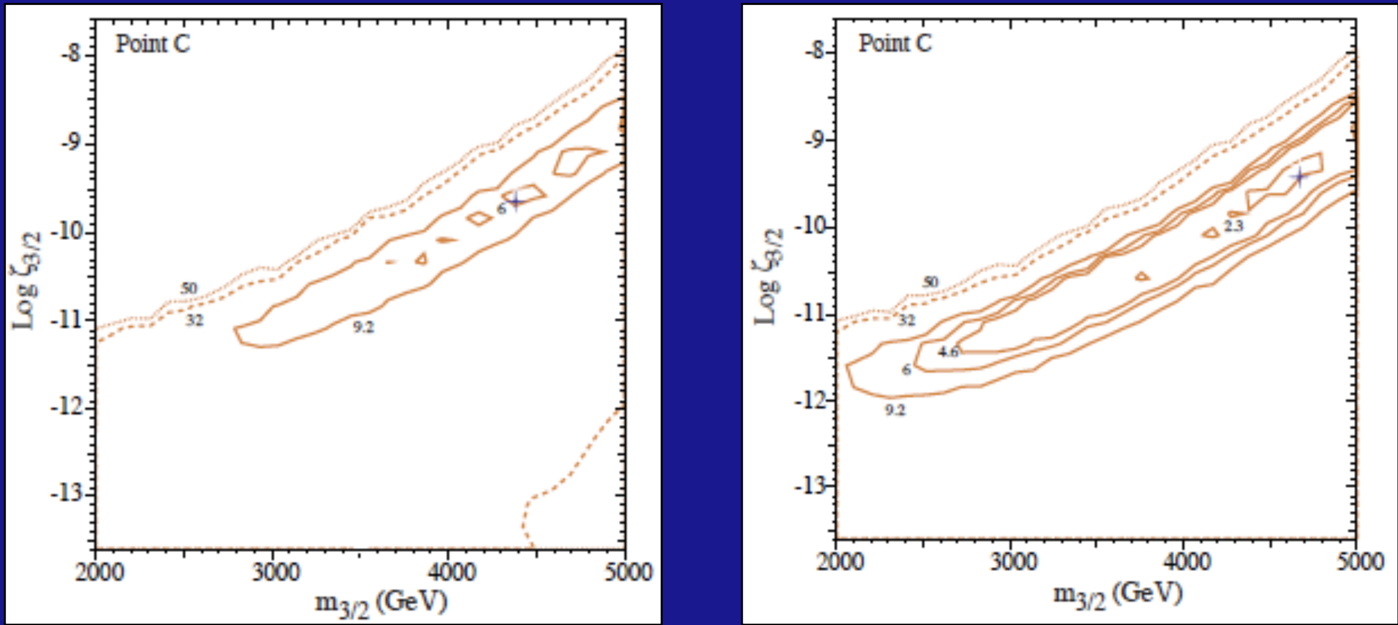
Table 1: Nuclear reactions of non-thermal particles, including the most important of the estimated uncertainties in the cross sections.

Code	Reaction	Uncertainty ϵ	Reference
1	$p^4\mathrm{He} \to d^3\mathrm{He}$		Meyer [34]
2	$p^4\mathrm{He} \to np^3\mathrm{He}$	20%	Meyer [34]
3	$p^4\mathrm{He} \to ddp$	40%	Meyer [34]
4	$p^4\mathrm{He} \to dnpp$	40%	Meyer [34]
5	$d^4\mathrm{He} \to {}^6\mathrm{Li}\gamma$		Mohr [35]
6	$t^4\mathrm{He} \to {}^6\mathrm{Li}n$	20%	Cyburt et al. [14]
7	${}^3\mathrm{He}^4\mathrm{He} \to {}^6\mathrm{Li}p$	20%	Cyburt et al. [14]
8	$t^4\mathrm{He} \to {}^7\mathrm{Li}\gamma$		Cyburt [27]
9	${}^3\mathrm{He}^4\mathrm{He} \to {}^7\mathrm{Be}\gamma$		Cyburt and Davids [36]
10	$p^6\mathrm{Li} \to {}^3\mathrm{He}^4\mathrm{He}$		Cyburt et al. [14]
11	$n^6\mathrm{Li} \to t^4\mathrm{He}$		Cyburt et al. [14]
12	$pn \to d\gamma$		Ando, Cyburt, Hong, and Hyun [37]
13	$pd \to {}^3\mathrm{He}\gamma$		Cyburt et al. [14]
14	$pt \to n^3\mathrm{He}$		Cyburt [27]
15	$p^6\mathrm{Li} \to {}^7\mathrm{Be}\gamma$		Cyburt et al. [14]
16	$p^7\mathrm{Li} \to {}^8\mathrm{Be}\gamma$		Cyburt et al. [14]
17	$p^7\mathrm{Be} \to {}^8\mathrm{B}\gamma$		Cyburt et al. [32]
18	$np \to d\gamma$		Ando, Cyburt, Hong, and Hyun [37]
19	$nd \to t\gamma$		Cyburt et al. [14]
20	$n^4\mathrm{He} \to dt$		Meyer [34]
21	$n^4\mathrm{He} \to npt$	20%	Meyer [34]
22	$n^4\mathrm{He} \to ddn$	40%	Meyer [34]
23	$n^4\mathrm{He} \to dnnp$	40%	Meyer [34]
24	$n^6\mathrm{Li} \to {}^7\mathrm{Li}\gamma$		Cyburt et al. [14]
25	n (thermal)		—
26	$n^7\mathrm{Be} \to p^7\mathrm{Li}$		Cyburt et al. [14]
27	$n^7\mathrm{Be} \to {}^4\mathrm{He}^4\mathrm{He}$		Cyburt et al. [32]
28	$p^7\mathrm{Li} \to {}^4\mathrm{He}^4\mathrm{He}$		Cyburt et al. [14]
29	$n\pi^+ \to p\pi^0$		Meyer [34]
30	$p\pi^- \to n\pi^0$		Meyer [34]
31	$p^4\mathrm{He} \to ppt$	20%	Meyer [34]
32	$n^4\mathrm{He} \to nn^3\mathrm{He}$	20%	Meyer [34]
33	$n^4\mathrm{He} \to nnnpp$		Meyer [34]
34	$p^4\mathrm{He} \to nnppp$		Meyer [34]
35	$p^4\mathrm{He} \to N^4\mathrm{He}\pi$		Meyer [34]
36	$n^4\mathrm{He} \to N^4\mathrm{He}\pi$		Meyer [34]

Cyburt, JE, Fields, Luo, Olive & Spanos: arXiv:1007.4173

Improvements in Fit to BBN Data

- Standard BBN: $\chi^2 = 31.7$
- Best fit to halo Li data: $\chi^2 \sim 5.5$

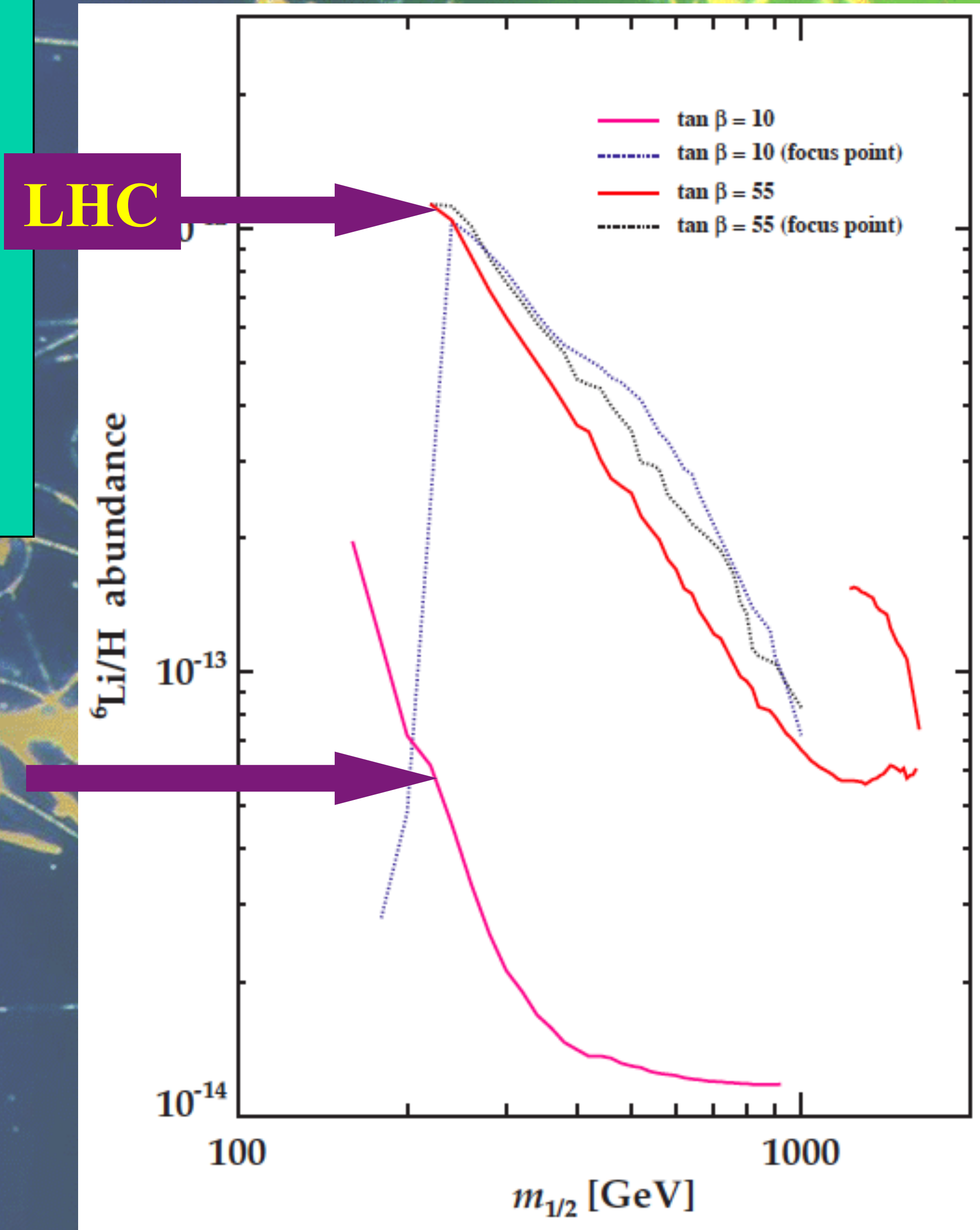


- Best fit to globular cluster Li data: $\chi^2 \sim 2.7$
- Allowing for higher D/H error: $\chi^2 \sim 1.1$

Cyburt, JE, Fields, Luo, Olive & Spanos: arXiv:1007.4173

Effect of Annihilations during Big-Bang Nucleosynthesis on ^{6}Li Abundance

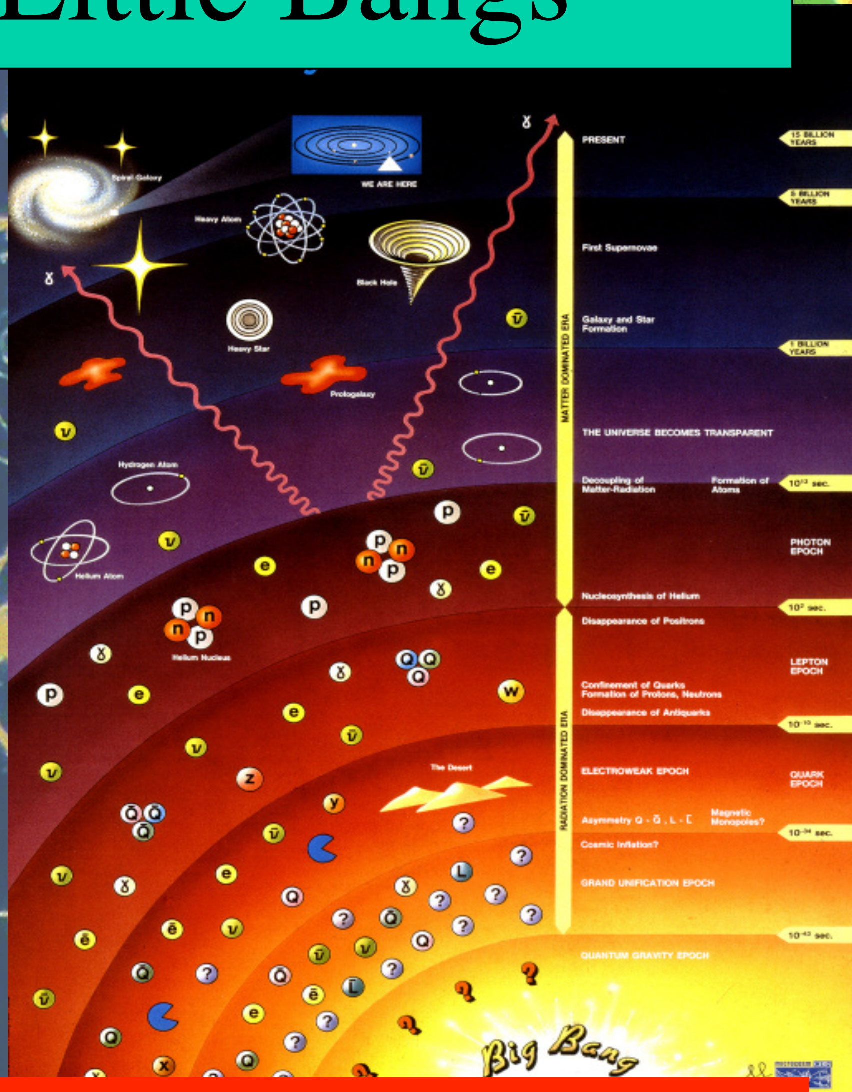
- Standard Big-Bang nucleosynthesis predicts ^{6}Li/H ~ 10^{-14}
- Some observations suggest enhancement to ^{6}Li/H ~ 10^{-11}
- Late dark matter annihilations may enhance to ^{6}Li/H ~ 10^{-12}



JE, Fields, Luo, Olive & Spanos: arXiv:1109.0549

Big Bang ↔ Little Bangs

- The content of the Universe
  - Dark energy
  - Dark matter
  - Origin of matter
- Particle experiments
  - Higgs boson
  - Supersymmetry
  - Matter-antimattter



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